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Research and Development

Lake Erie Nutrient Control Program

An Assessment of Its Effectiveness in Controlling Lake Eutrophication

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July 1980

LAKE ERIE NUTRIENT CONTROL PROGRAM

An Assessment of Its Effectiveness in Controlling Lake Eutrophication

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FOREWORD

The Great Lakes comprise approximately 20 percent of the world's fresh water supply; therefore, it is of critical importance to protect the Great Lakes for their various uses. Of all the Great Lakes, Lake Erie has been stressed to the furthest extent as a result of man's activities. This report provides an insight into the processes that go on within Lake Erie and our attempt to describe them. As we better describe the processes that go on within the Great Lakes, we will be in a better position to understand and predict the management of Great Lakes systems.

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ABSTRACT

A three-year assessment of nutrient control efforts was conducted in the western and central basins of Lake Erie during the period June 1973 to June 1976. The objective of the study was to determine recent trends in lake eutrophication and water quality which may be related to recent attempts to control nutrient loadings to these basins. The assessment was accomplished by visiting approximately 50 stations at nearly monthly intervals during the ice-free periods. Over 25 water quality, meteorological and biological parameters were routinely determined shipboard or on samples collected at a typical station. Measurements were taken at several depths in order to characterize the various strata of water in the lake and to permit volume-weighted calculation of nutrient concentrations and quantities. Data from previous limnological surveys as far back as 1928 were compared with the results of the present study to establish long-term trends, as well as recent trends since the last comprehensive survey in 1970.

The fundamental conclusion of this assessment is that during the first half of this decade no significant decrease in the loading of nutrients to Lake Erie has taken place. Therefore, during this period the concentrations and quantities of nutrients within the waters of the lake have remained relatively stable. An encouraging sign of nutrient control is that although no decreases have been observed, the constant increases which have taken place in preceeding decades have been stopped. Other indicators of eutrophication, such as hypolimnetic oxygen depletion rates, chlorophyll concentrations, methane production, plankton and benthos populations, dissolved solids and turbidity, have remained high since 1970 but also relatively stable.

Most of the nutrient loading to Lake Erie occurs in the western basin. The largest quantity is delivered by the Detroit River, but the highest concentrations were observed near the mouth of the Maumee River. The western and central basins are effective sinks for nutrient loading; approximately 82 percent of the phosphorus carried to the lake by the tributaries remains in bottom sediments. Up to 10 percent of the phosphorus delivered to the lake can be regenerated under anoxic conditions. However, physical regeneration due to storm resuspension of sediment can have a larger impact on internal nutrient loading, particularly during non-stratified periods.

Meteorological variations, such as wind, solar radiation and precipitation, appear to have a much more profound effect on the trophic status of Lake Erie than attempts at nutrient control. For example, in 1975 light winds during the period of thermocline formation resulted in a thicker hypolimnion in the central basin. This increased reservoir of oxygen reduced the area of anoxia by over 95 percent and thereby decreased the amount of regenerated phosphorus from the sediments by over 70 percent from the previous two years. Also, because of high concentrations of nutrients in the lake, particularly the western basin, the limiting factor in algal production appears to be sunlight. Precipitation also plays a role in nutrient concentrations; high rainfall in the early 1970's over the upper Great Lakes basins resulted in record-high flow rates in the Detroit River in 1972 and 1973. The concentration of nutrients, although not the quantity, was lowest during this period from dilution by excessive precipitation.

Although the effectiveness of nutrient controls in reversing eutrophication in Lake Erie cannot be demonstrated, the halting of further degradation is an important first step. Also, many new treatment facilities are just now being placed in operation. Modifications in agricultural practices will reduce the loading of nutrients to the tributaries, but these changes will not be reflected in water quality improvements for several years due to the slow migration of sediment to the lake. It is important that this start at improving the conditions of Lake Erie be continued and that new methods of lake restoration be explored.

This report was submitted in fulfillment of Grant No. R802543 by The Ohio State University, Center for Lake Erie Area Research, under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 15, 1973 to June 14, 1976 and work was completed as of April 27, 1979.

CONTENTS

Foreword iii
Abstract iv
Figures viii
Tables xix
Acknowledgements xxvi

1. Lake Erie Nutrient Control Assessment: An Overview of the Study
Charles E. Herdendorf 1
2. History of Lake Erie Water Quality
Clarence E. Taft 64
3. Oxygen Depletion and Anoxia in the Central and Western Basins of Lake Erie, 1973-1975
John E. Zapotosky and Charles E. Herdendorf . . . 71
4. Transparency, Conductivity and Temperature Surveys in the Central and Western Basins of Lake Erie
John E. Zapotosky 103
5. Lake Erie Winds: A Preliminary Analysis 1973-1975
Daniel L. Wise 118
6. Phosphorus Budget of the Central and Western Basins Of Lake Erie: 1973-1975
Karlis Svanks 131
7. Chlorophyll a and Pheopigment Distribution in the Central and Western Basins of Lake Erie
Laura A. Fay and David E. Rathke 175
8. Primary Productivity Survey of the Central and Western Basins of Lake Erie
Clifford T. Sheffield and Walter E. Carey 231
9. Zooplankton Distribution in the Central and Western Basins of Lake Erie
Donna D. Larson and David E. Rathke 272
10. Benthic Macroinvertebrate Distribution in the Central and Western Basins of Lake Erie
N.W. Britt, A.J. Pliodzinskas and E.M. Hair . . 294
11. Statistical Analysis of the 1975 Intercomparison Study on Lake Erie
Paul I. Feder and John E. Zapotosky 331

FIGURES

Number		Page
1	Monitoring stations location map for the central and western basins of Lake Erie	4
2	Schematic representation of sampling depths in Lake Erie	12
3	Water quality grids used for area- and volume-weighted calculations in the central and western basins of Lake Erie	14
4	Trends in anoxic hypolimnion of Lake Erie 1930-1974.	16
5	Relationship between dissolved oxygen concentrations in the lower hypolimnion of central Lake Erie and soluble reactive phosphorus regeneration, cruises 7 and 8, August 12-September 5, 1974 . .	21
6	Concentration of soluble reactive phosphorus and dissolved oxygen in the central basin hypolimnion of Lake Erie - 1974	22
7	Bottom dissolved oxygen, cruise 4, August 27-September 7, 1975	24
8	Daily resultant wind at Long Point, Ontario for April, May and June 1973-1975	27
9	Quantity of phosphorus in Lake Erie, 1970-1975 . . .	29
10	Total phosphorus concentrations in Lake Erie, 1970-1975	30
11	Total phosphorus concentrations in Lake Erie, 1973-1975	34

FIGURES CON'T

Number		Page
12	Total phosphorus quantity in Lake Erie, 1973-1975	34
13	Volume weighted quantity (metric tons) of total phosphorus in Lake Erie 1974-1975	36
14	Soluble reactive phosphorus concentrations in Lake Erie, 1974-1975	37
15	Soluble reactive phosphorus quantity in Lake Erie, 1974-1975	37
16	Concentration of chlorophyll a in Lake Erie surface water, 1973-1975	45
17	Trends in Lake Erie surface water chlorophyll 1967-1974	45
18	Volume weighted concentration (ug/l) of corrected chlorophyll a in Lake Erie 1973-1975	47
19	Volume weighted quantity (metric tons) of corrected chlorophyll a in Lake Erie 1973-1975	47
20	Total phytoplankton populations at Put-in-Bay	54
21	Bacillariophycean populations at Put-in-Bay	54
22	Chlorophycean populations at Put-in-Bay	55
23	Myxophycean populations at Put-in-Bay	55
24	Bottom dissolved oxygen, cruise 1, March 18-April 25, 1975	72
25	Bottom dissolved oxygen, cruise 2, June 2-June 19, 1975	72
26	Bottom dissolved oxygen, cruise 3, July 13-July 24, 1975	73

FIGURES CON'T

Number Page

27 Bottom dissolved oxygen, cruise 4, August 27-September 7, 1975 73

28 Bottom dissolved oxygen, cruise 5, September 27-October 6, 1975 77

29 Bottom dissolved oxygen, Cruise 6, December 2-December 10, 1975 77

30 Temperature profile at station no. 73 for May-October 1974 79

31 Temperature profile at station no. 73 for April-December 1975 79

32 Volume comparison for stratification layers in the central basin of Lake Erie 1973-1975 80

33 Thermal structure of Lake Erie (^{o}C), profile H, cruise 5, September 3, 1973 81

34 Thermal structure of Lake Erie (^{o}C), profile F, cruise 1, June 30-July 1, 1973 82

35 Thermal structure of Lake Erie (^{o}C), profile G, cruise 4, August 9, 1973 83

36 Bottom dissolved oxygen, cruise 4, August 7-August 11, 1973 84

37 Bottom dissolved oxygen, cruise 6, July 26-August 6, 1974 84

38 Mean volumetric dissolved oxygen depletion rate for the hypolimnion of the central basin of Lake Erie 1929-1975 89

39 Monthly wind persistence for dominant direction at Long Point, Ontario for 1974 and 1975 93

FIGURES CON'T

Number Page

40 Average and resultant winds at Long Point, Ontario for 1973-1975 93

41 Long Point winds for 1973, 1974 and 1975 94

42 Mean monthly air and water temperatures at Marblehead, Ohio for 1973-1974 97

43 Bottom dissolved oxygen, cruise 1, July 10-12, 1973 99

44 Bottom dissolved oxygen, cruise 5, August 20-30, 1973 99

45 Average-area weighted Secchi depth (M) 104

46 Great Lakes basin average monthly precipitation . . . 106

47 Lake Erie basin average monthly precipitation 107

48 Specific conductance in Lake Erie 1974 109

49 Specific conductance in Lake Erie 1975 110

50 Specific conductance in Lake Erie. 112

51 Air and water temperatures at Put-in-Bay, Ohio 1973 113

52 Air and water temperatures at Put-in-Bay, Ohio 1974 114

53 Monthly resultant wind velocities for Long Point, Ontario 127

54 Histogram of resultant winds at Long Point, Ontario, April-June 1973-1975 127

55 Transects for phosphorus concentration gradient calculations 138

FIGURES CON'T

Number Page

56 Epilimnetic phosphorus concentration gradient for Lake Erie central basin 141

57 Lake Erie central basin - 1975, phosphorus transformation 170

58 Regeneration and sedimentation rates of particulate phosphorus in the central and western basins of Lake Erie - 1975 170

59 Basin subdivisions used for chlorophyll analysis 1973-1975 182

60 Central basin subdivisions used for chlorophyll analysis, 1973-1975 182

61 Average corrected chlorophyll a (µg/l) by station, 1973-1975 185

62 Average corrected chlorophyll a (µg/l) at central basin stations, 1973-1975 185

63 Corrected chlorophyll a (µg/l) station means for 1973-1975 187

64 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 2, July 17-July 24, 1973 190

65 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 5, August 29-September 4, 1973 191

66 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 7, October 14-October 24, 1973 192

67 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 2, April 25-May 4, 1974 193

FIGURES CON'T

Number Page

68 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 4, June 1-June 10, 1974 194

69 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 5, June 28-July 7, 1974 195

70 Correctec chlorophyll a (µg/l) average for all depths sampled, cruise 7, August 12-August 19, 1974 196

71 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 8, August 26-September 7, 1974 197

72 Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 10, October 21-November 1, 1974. 198

73 Corrected chlorophyll a (µg/l), cruise 1A and 1B, March 27-April 25, 1975 199

74 Corrected chlorophyll a (µg/l), cruise 2, June 9-June 19, 1975 200

75 Corrected chlorophyll a (µg/l), cruise 3, July 13-July 21, 1975 201

76 Corrected chlorophyll a (µg/l), cruise 4, August 30-September 5, 1975 202

77 Corrected chlorophyll a (µg/l), cruise 5, September 27-October 6, 1975 203

78 Corrected chlorophyll a (µg/l), cruise 6, December 2-December 14, 1975 204

79 FWPCA station locations, 1967-1968. 212

FIGURES CON'T

Number Page

80 Comparison of central and western basin chlorophyll a values (average of surface and mid-depth values) from FWPCA, 1967 data and corresponding 1974 and 1975 data 213

81 CLEAR stations enclosed in boxes used for comparisons with Glooschenko's 1970 chlorophyll study 214

82 Comparison of central basin chlorophyll a values from Glooschenko's 1970 data and corresponding 1974 and 1975 data. 219

83 Comparison of western basin chlorophyll a values from Glooschenko's 1970 data and corresponding 1974 and 1975 data. 219

84 Particulate organic carbon and corrected chlorophyll a concentrations - Lake Erie central and western basins, 1973-1975 222

85 Particulate organic carbon and corrected chlorophyll a tonnages, Lake Erie central and western basins, 1973-1975 223

86 Lake Erie central basin surface water - 1975: corrected chlorophyll a, particulate phosphorus and particulate organic carbon concentrations, area weighted 224

87 Lake Erie central basin bottom water - 1975: corrected chlorophyll a, particulate phosphorus and particulate organic carbon concentrations, area weighted 225

88 Lake Erie central basin bottom water - 1975 226

89 Lake Erie central basin surface water - 1975 226

FIGURES CON'T

Number Page

90 Map of Lake Erie showing station locations in the central and western basins 233

91 Relationship of *in situ* productivity to relative light intensity near Rattlesnake Island 244

92 Relationship of relative *in situ* productivity and light transmission of depth near Rattlesnake Island 245

93 Relationship of sample activity to aliquot volume . . 246

94 Relationship of sample activity to time after fixation 246

95 Vertical profile of incubator productivity at station 47 on 30 July 1974 and station 23 on 13 August 1974 249

96 Vertical profile of incubator productivity at station 25 on 13 August 1974 and station 30 on 1 August 1974 251

97 Vertical profile of incubator productivity at station 30 on 14 August 1974 and station 39 on 27 October 1974 252

98 Vertical profile of incubator productivity at station 48 on 4 August 1974 and 16 August 1974 253

99 Vertical profile of incubator productivity at station 52 on 27 July 1974 and station 73 on 30 July 1974 254

100 Relationship of incubator productivity to uncorrected chlorophyll *a* concentration at 1 M depth. 256

FIGURES CON'T

Number Page

101 Relationship of incubator productivity to total phosphorus concentration at 1 M depth 256

102 Relationship of mean relative dark ^{14}C uptake to mean incubator productivity at each station in central and western Lake Erie. 263

103 Relationship of relative dark ^{14}C uptake to light transmission 265

104 Sub-basin map 274

105 Zooplankton collecting stations 1967-1968 274

106 1970 zooplankton collecting stations 276

107 1968 zooplankton collecting stations 276

108 Average zooplankton concentrations in no./m^3 by sub-basin 278

109 Average rotifer concentrations in no./m^3 by sub-basin 282

110 Average cladoceran concentrations in no./m^3 by sub-basin 285

111 Average copepod concentrations in no./m^3 by sub-basin 287

112 Average benthic macroinvertebrate diversity 300

113 Distribution of surficial sediments 300

114 Prevailing annual bottom flow 301

115 Lake Erie bathymetry 301

116 Average percent oligochaeta in the bottom fauna . . . 303

FIGURES CON'T

Number Page

117 Average benthic macroinvertebrate densities (indiv./m^2) for central and western basins of Lake Erie 1973-1974 303

118 Average oligochaete density for central and western basins of Lake Erie 1973-1974 304

119 Average percent oligochaetes in the bottom fauna. . . 304

120 Average chironomid density in central and western basins of Lake Erie 1973-1974 305

121 Average percent of chironomidae in the bottom fauna 305

122 Average sphaeriid density in the central and western basins of Lake Erie 1973-1974 307

123 Average percent of sphaeridae in the bottom fauna . . 307

124 Average oligochaete diversity in the central and western basins of Lake Erie 1973-1974 308

125 Distribution of Limnodrilus species in the central and western basins of Lake Erie 1973-1974 . . . 309

126 Distribution of Oligochaete species in the central and western basins of Lake Erie 1973-1974 . . . 310

127 Distribution of Oligochaete species in the central and western basins of Lake Erie 1973-1974 . . . 311

128 Distribution of mollusca in the central and western basins of Lake Erie 1973-1974 313

129 Distribution of chironomidae in the central and western basins of Lake Erie 1973-1974 315

130 Distribution of minor elements in the central and western basins of Lake Erie 1973-1974 316

FIGURES CON'T

Number		Page
131	Distribution of organic carbon in surficial sediments (% dry weight)	317
132	Bottom dissolved oxygen, cruise 5, August 29-September 4, 1973	317
133	Average density changes in central and western basins (1973-1974) during ice-free months	320
134	Average diversity changes in central and western basins (1973-1974).	320
135	Bottom dissolved oxygen, cruise 7, August 12-19, 1974	321
136	Bottom dissolved oxygen, cruise 8, August 26-September 7, 1974	321
137	Extent of organic pollution indicated by tubificid index (Wright, 1955)	324
138	Lake Erie benthic population distribution 1963-1964. .	325
139	Average density Lake Erie benthic populations 1963-1964.	326
140	Average density benthic macroinvertebrates in western and central Lake Erie 1973-1974	326
141	Temperature profile (^{o}C) Secchi depths and sampling sites	333

TABLES

Number Page

1 Limnological Parameters Monitored in the Central and Western Basins of Lake Erie 3

2 Geographical Coordinates for Stations in the Central and Western Basins of Lake Erie 5

3 Lake Erie Cruise Schedules for 1973-1975 7

4 Stations Occupied in the Central and Western Basins of Lake Erie in 1973-1975 8

5 System of Parameters Used to Index the State of Eutrophication in Lake Erie 9

6 Estimated Area of the Anoxic Hypolimnion of the Central Basin of Lake Erie 1930-1974 17

7 Trends in Net Oxygen Demand of the Central and Eastern Basin Hypolimnions of Lake Erie . . 19

8 Comparison of 1973, 1974 and 1975 Characteristics of Hypolimnion in Central Lake Erie 25

9 Phosphorus Budget for the Western and Central Basins of Lake Erie, May-September 1970-1975 . 31

10 Concentration and Quantity of Total Phosphorus in Western and Central Lake Erie - 1975 33

11 Ten-Year Comparison of Mean Water Quality in Lake Erie 43

12 Average Surface Chlorophyll a in Lake Erie - 1973 46

TABLES CON'T

Number Page

13 Ratio of Chlorophyll a Concentration in Western and Central Basins of Lake Erie 1973-1975 48

14 Summary of 1973 Hypolimnetic Surveys of the Central Basin of Lake Erie 74

15 Summary of 1974 Hypolimnetic Surveys of the Central Basin of Lake Erie 75

16 Summary of 1975 Hypolimnetic Surveys of the Central Basin of Lake Erie 76

17 Sample Calculation for Mesolimnion Exchange Model for Lake Erie Hypolimnion Oxygen Depletion for July 16-September 1, 1975 85

18 Hypolimnetic Oxygen Depletion Rates in the Central Basin of Lake Erie (1973-1975) 87

19 Hypolimnetic Oxygen Central Basin of Lake Erie 1974 and 1975 Values = $kgO_2 \times 10^6$ 92

20 Monthly Average Air-Water Temperature Difference °C - Marblehead and Put-in-Bay, Ohio 96

21 Specific Conductance in the Central and Western Basins of Lake Erie, 1974-1975 108

22 Results of the Wind Analysis for Various Periods at Long Point, Ontario: 1973-1975 124

23 Percent Frequency of the 8-Point Wind Directions Derived from Hourly Wind Data for Long Point, Ontario, April-December, 1973-1975 126

24 Concentration and Quantities of Phosphorus Forms in Lake Erie Central Basin 133

25 Total Phosphorus Input in Lake Erie Metric Tons . . 135

TABLES CON'T

Number		Page
26	Lake Erie Western and Central Basin Average Daily Total and Soluble Reactive Phosphorus Loads Metric Tons - 1975	136
27	Flow Rates of Water into Lake Erie	137
28	Average Phosphorus Concentration in Lake Erie Central Basin at Transects 1 through 6 in PPB . .	140
29	CLEAR Nutrient Cruise Timetable	144
30	Lake Erie Western Basin Total Phosphorus Budget (Metric Tons) July 17-October 24, 1973	145
31	Lake Erie Central Basin Total Phosphorus Budget (Metric Tons) July 17-October 24, 1973	147
32	Lake Erie Western plus Central Basin Total Phosphorus Budget (Metric Tons) July 17-October 24, 1973	149
33	Lake Erie Western Basin Total Phosphorus Budget (Metric Tons) April 25-November 1, 1974	150
34	Lake Erie Central Basin Total Phosphorus Budget (Metric Tons) April 25-November 1, 1974	151
35	Lake Erie Western plus Central Basin Total Phosphorus Budget (Metric Tons) April 25-November 1, 1974	153
36	Lake Erie Western Basin Total Phosphorus Budget (Metric Tons) March 27-December 14, 1975 . . .	154
37	Lake Erie Central Basin Total Phosphorus Budget (Metric Tons) March 27-December 14, 1975 . . .	155
38	Lake Erie Western plus Central Basin Total Phosphorus Budget (Metric Tons) March 27-December 14, 1974	158

TABLES CON'T

Number Page

39 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 1-2 159

40 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 2-3 160

41 Lake Erie Central Basin 1975 Phosphorus Budgets, Metric Tons - Cruise 2-3 161

42 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 3-4 162

43 Lake Erie Central Basin 1975 Phosphorus Budgets, Metric Tons - Cruise 3-4 163

44 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 4-5 164

45 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 5-6 165

46 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 5-6 166

47 Lake Erie Central Basin 1975 Phosphorus Budget, Metric Tons - Cruise 1-6 167

48 Lake Erie and Central Basin 1970-1975, May through September (5/1-9/30) Mean Total Phosphorus Concentration and Quantities, "Anoxic" Regeneration, External Loading and Sink 171

49 Total Phosphorus "Anoxic" Regeneration Associated with Anoxic Hypolimnion Lake Erie Western and Central Basin - 1973, 1974 and 1975 173

50 Equations used for Lake Erie--1973-1975 Calculations 177

TABLES CON'T

Number Page

51 Corrected Chlorophyll a - Volume Weighted Concentrations, 1973-1975 180

52 Corrected Chlorophyll a - Volume Weighted Concentrations, 1973-1975 183

53 Corrected Chlorophyll a - Station Means for the 15 Cruises, 1973-1975 184

54 Percent of Annual Total Corrected Chlorophyll a and Pheopigment a Contributed at Each Cruise Interval - Central Basin 188

55 Percent of Annual Total Corrected Chlorophyll a and Pheopigment a Contributed at Each Cruise Interval - Western Basin 189

56 Corrected Chlorophyll a and Pheopigment a - Central Basin 205

57 Corrected Chlorophyll a and Phoepigment a - Western Basin, 1973-1975 207

58 Similar Stations from Chlorophyll Surveys Undertaken by the Federal Water Pollution Control Agency (1968) and the Center for Lake Erie Area Research, 1974-1975 210

59 Similar Stations from Chlorophyll Surveys in Glooschenko (1970) and CLEAR (1973-1975) . . . 215

60 Average Chlorophyll a (ug/l) in Lake Erie 1970 by Month and Western to Central Basin Ratios . . 216

61 CLEAR SCOR/UNESCO Chlorophyll a Concentrations Based on Stations Similar to Glooschenko's 1970 Survey (Surface and Mid-Values Only) . . . 217

TABLES CON'T

Number		Page
62	CLEAR SCOR/UNESCO Chlorophyll a (ug/l) Volume Weighted Concentrations. Basin Values Include all Stations at all Depths	220
63	Comparison of Primary Productivity Measurements in Central and Western Lake Erie from 1957-1974	240
64	Carbon Assimilation Rates by Station and Cruise for Central and Western Lake Erie in 1974	241
65	Mean Productivity by Basin from July-October 1974	242
66	Vertical Distribution of Uncorrected Chlorophyll a Concentration at Stations 30 and 36 in August 1974	250
67	Mean Secchi Disc and Euphotic Zone Depths for Central and Western Lake Erie from July-October 1974	258
68	Lake Erie Zooplankton Studies - Comparative Methods	277
69	Average 1974 Zooplankton Numbers/m^3 by Basin and Cruise	279
70	Zooplankton Species Found in Western and Central Basins of Lake Erie, 1974 and 1975	280
71	Sampling Periods for Lake Erie Nutrient Study - Benthos Cruises	295
72	Taxanomic Groups found in Lake Erie's Western and Central Basins During Lake Erie Nutrient Study (1973-1974)	297

TABLES CON'T

Number Page

73 Benthic Fauna Found in Lake Erie's Western and Central Basins 298

74 Benthic Macroinvertebrate Diversity in Lake Erie's Western and Central Basins During Lake Erie Nutrient Study (1973-1974) 299

75 Comparison of Density and Diversity (Taxa Number/m^2) for the Western and Central Basins, 1973-1974 . 319

76 Lake Erie Western Basin Bottom Fauna 1929-1930 Wright (1955) 323

77 Physical and Chemical Parameter Determinations Made by GLL, CCIW, CLEAR 334

78 Summary of Operational Details of 1975 Lake Erie Intercomparison 335

79 Basic Data on Six Chemical Properties of Water Samples 340

80 Overall Average Determinations by Site 344

81 Subsample, Whole Sample, Pump-to-Pump Variances - By Site 346

82 Analysis Group Averages - By Site 347

83 Sampling Group Averages - By Site 349

84 Sampling Depth Averages - By Site 350

85 Comparison of CLEAR Pump and Water Bottle Measurements - By Site 352

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SECTION 1

LAKE ERIE NUTRIENT CONTROL ASSESSMENT: AN OVERVIEW OF THE STUDY

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INTRODUCTION

In June 1973, the Center for Lake Erie Area Research (CLEAR) at The Ohio State University initiated a comprehensive, three-year monitoring orogram of biological and water quality parameters in the central and western basins of Lake Erie. At the same time a companion study was started in the eastern basin by the Great Lakes Laboratory (GLL) of the New York State University College at Buffalo. These studies, sponsored by the U.S. Environmental Protection Agency, are part of the Large Lakes Research Program (Grosse Ile) of EPA's Environmental Research Laboratory (Duluth). The studies were designed to examine several indicators of the trophic status of Lake Erie and develop a system to index the state of eutrophication in the lake as a function of inputs and time. The objective of the investigations is to determine the effectiveness of the various federal, state, and local nutrient control programs in halting the accelerated rate of Lake Erie eutrophication.

The water from Lake Erie sustains the vast industrial complex which extends from Detroit to Buffalo. Water returned to the lake is highly enriched by municipal, agricultural, and industrial waste products. Studies conducted in the late 1920's revealed that the lake was already moderately rich in nutrients and was experiencing phytoplankton blooms in its western basin. Adjacent to the Detroit River mouth sensitive mayflies were being replaced by tubificid worms. By the mid-1950's thermal stratification was resulting in oxygen depletion in the bottom water and mayfly nymphs suffered catastrophic mortality. The concentration of all the major ions, including the nutrients phosphorus and nitrogen, showed a marked increase during this period of time.

The concept of nutrient control for Lake Erie appears to have had its origin in 1965, when the U.S. Department of Health, Education and Welfare convened a conference on the pollution of Lake Erie and its tributaries under the authority granted in the Water Pollution Control Act of 1961. One of the recommendations forthcoming from the conference was that a "technical committee" be established to evaluate water quality problems related to nutrients in Lake Erie and to make recommendations to the conferees. In late 1965 the Lake Erie Enforcement Technical Committee was formally established to explore the problems related to nutrients and over-enrichment of Lake Erie. The committee received information and advice from leading authorities in water-oriented disciplines, and after a year of study a final report was issued. The report concluded that the major pollution problems in Lake Erie results directly or indirectly from excess algae and that these growths are stimulated by nutrients resulting from man's activities.

The technical committee recommended that water quality objectives be established that would prevent nuisance algae conditions, particularly by lowering the phosphate and nitrogen levels in the lake. The committee further recommended that new treatment processes be developed and employed to effect high phosphate removal. Based on these recommendations the Federal Water Pollution Control Administration (FWPCA) later the Federal Water Quality Administration (FWQA), and more recently the Environmental Protection Agency (EPA), as well as state and local agencies, have embarked on a program to control the flow of nutrients to Lake Erie. The necessity for this control has been reinforced by recent findings of the International Joint Commission and the Canada-United States Water Quality Agreement of 1972.

STUDY PLAN

In order to assess the success of these efforts a study plan was developed to monitor over 20 limnological parameters (Table 1) at approximately 50 stations in the central and western basins of Lake Erie. The station locations were selected to correlate with previous limnological studies, e.g. Project Hypo--a joint USEPA/Canada Centre for Inland Waters (CCIW) study of central Lake Erie in 1970 (Burns and Ross, 1972), and to monitor areas of nutrient loading and the subsequent dispersal of these substances throughout the basins (Figure 1 and Table 2).

In order to sample this large area, a vessel of sufficient size to carry both scientific equipment and crew for extended periods of time was required. During the 1973 season several boats were employed on this study: R/V Dambach (Great Lakes Laboratory, SUNY), the R/V

TABLE 1. LIMNOLOGICAL PARAMETERS MONITORED IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

Parameter	Determination Method
1. Shipboard Sensors	
a. Temperature	BT/Submersible probe (Martek)
b. Conductivity	Submersible probe (Martek)
c. Dissolved Oxygen	Submersible probe (Martek)
d. pH	Submersible probe (Martek)
e. Transparency	Secchi disk
f. Transmissibility	Transmissometer (Martek)
g. Light Penetration	Photometer (Lambda)
2. Shipboard Laboratory	
a. Alkalinity	Titration (HCl)
b. Ammonia Nitrogen	AutoAnalyzer (Technicon)
c. Chloride	AutoAnalyzer (Technicon)
d. Dissolved Silica	AutoAnalyzer (Technicon)
e. Nitrate + Nitrite	AutoAnalyzer (Technicon)
f. Sol. Reactive Phosphorus	AutoAnalyzer (Technicon)
g. Total Phosphorus	AutoAnalyzer (Technicon)
3. Mainland Laboratory	
a. Particulate Organic Carbon	Elemental analyzer (Perkin-Elmer)
b. Particulate Organic Nitrogen	Elemental analyzer (Perkin-Elmer)
c. Chlorophyll *a*, *b*, *c*, and Pheopigments	Spectrophotometer (Varian Techtron)
d. Primary Productivity	Shipboard incubation/^{14}C, GM counter
e. Phytoplankton Populations	Niskin bottle/Inverted microscope
f. Zooplankton Populations	Vertical net tow/Dissecting microscope
g. Benthic Macroinvertebrate Populations	Ponar dredge/Dissecting microscope
h. Methane Production (microbial)	Gas chromatograph (Varian)
i. Nitrogen Fixation (microbial)	Gas chromatograph (Varian)

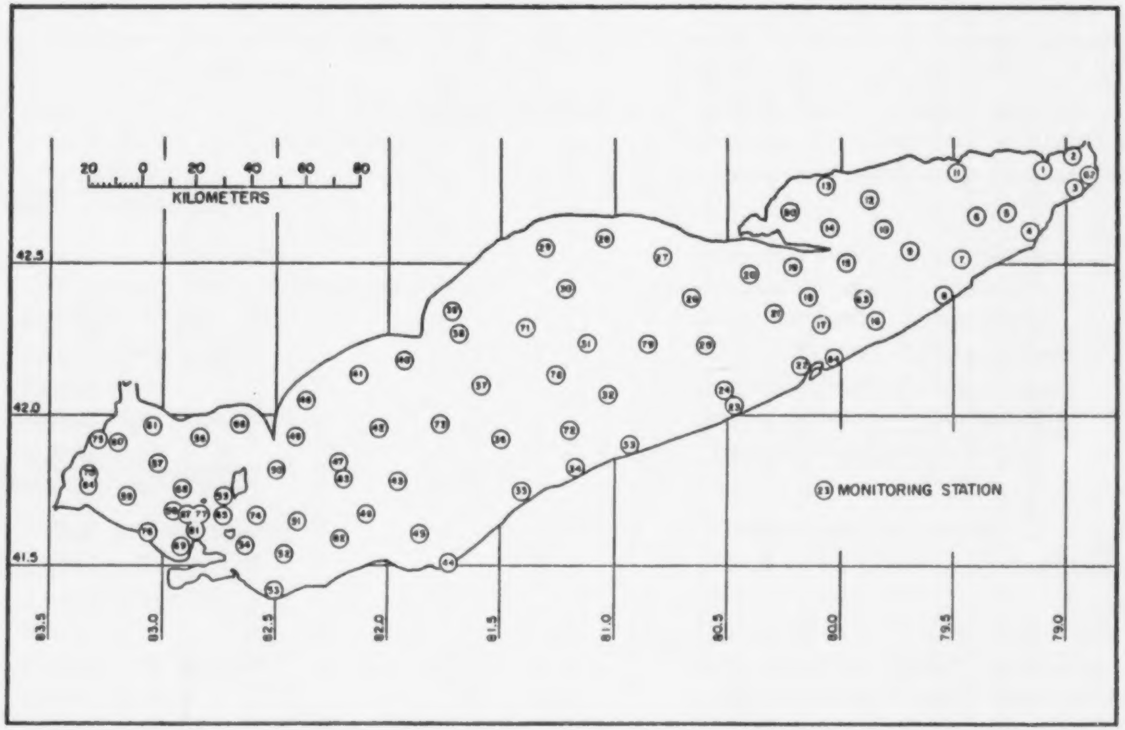

20
0
20
40
60
80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
23 MONITORING STATION

Figure 1. Monitoring stations location map for the central and western basins of Lake Erie.

TABLE 2. GEOGRAPHICAL COORDINATES FOR STATIONS IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

Station No.	Latitude (North)	Longitude (West)	Basin	Grid No.
23	42° 02' 48"	80° 27' 0 "	C	19
24	42° 05' 54"	80° 29' 00"	C	19
25	42° 14' 54"	80° 33' 36"	C	20
26	42° 24' 00"	80° 38' 12"	C	20
27	42° 32' 54"	80° 45' 30"	C	21
28	42° 35' 30"	81° 01' 00"	C	22
29	42° 36' 18"	81° 17' 54"	C	22
30	42° 25' 48"	81° 12' 18"	C	23
31	42° 15' 12"	81° 06' 24"	C	24
32	42° 04' 54"	81° 00' 42"	C	25
33	41° 55' 54"	80° 55' 00"	C	26
34	41° 50' 00"	81° 08' 54"	C	26
35	41° 45' 48"	81° 23' 00"	C	27
36	41° 56' 06"	81° 28' 42"	C	28
37	42° 06' 36"	81° 34' 30"	C	29
38	42° 16' 54"	81° 40' 18"	C	30
39	42° 21' 30"	81° 42' 24"	C	31
40	42° 11' 30"	81° 55' 18"	C	32
41	42° 08' 06"	82° 08' 24"	C	32
42	41° 57' 54"	82° 02' 30"	C	33
43	41° 47' 18"	81° 56' 42"	C	34
44	41° 31' 48"	81° 42' 30"	C	36
45	41° 36' 24"	81° 53' 48"	C	35
46	41° 40' 54"	82° 05' 12"	C	37
47	41° 50' 18"	82° 12' 48"	C	38
48	42° 02' 48"	82° 21' 54"	C	39
49	41° 55' 54"	82° 24' 30"	C	39
50	41° 48' 48"	82° 30' 06"	C	40
51	41° 38' 30"	82° 24' 12"	C	41
52	41° 31' 54"	82° 27' 12"	C	43
53	41° 25' 12"	82° 30' 12"	C	42
54	41° 34' 00"	82° 38' 06"	C	43
55	41° 44' 18"	82° 44' 00"	W	44
56	41° 54' 42"	82° 50' 24"	W	45
57	41° 49' 54"	83° 01' 06"	W	48
58	41° 41' 06"	82° 56' 00"	W	46
59	41° 43' 36"	83° 09' 00"	W	47
60	41° 53' 30"	83° 11' 48"	W	49
61	41° 56' 48"	83° 02' 42"	W	50
65	41° 39' 00"	82° 44' 00"	W	43
66	41° 58' 00"	82° 40' 00"	W	45
67	41° 40' 00"	82° 52' 00"	W	46
68	41° 45' 00"	82° 51' 00"	W	46
69	41° 33' 00"	82° 55' 00"	W	46
70	41° 46' 00"	83° 20' 00"	W	49
71	42° 18' 00"	81° 22' 20"	C	23
72	41° 57' 50"	81° 11' 00"	C	26
73	41° 58' 40"	81° 45' 25"	C	34
74	41° 40' 00"	82° 35' 00"	C	43
75	41° 54' 00"	83° 18' 00"	W	49
76	41° 36' 30"	83° 04' 00"	W	46
77	41° 39' 30"	82° 49' 36"	W	46
78	42° 07' 00"	81° 15' 00"	C	24
79	42° 15' 00"	80° 48' 00"	C	20
81	41° 36' 36"	82° 50' 40"	C	46
82	41° 34' 30"	82° 10' 00"	C	41
83	41° 42' 30"	82° 19' 10"	C	38
84	41° 45' 36"	83° 19' 42"	W	47

Maple (Great Lakes Research Division, University of Michigan), the P/B Bluewater (Grosse Ile Laboratory, USEPA), and the R/V Hydra (CLEAR, Ohio State University). The latter vessel, a modified U.S. Army cargo lighter leased from USEPA (Region V), was outfitted with a nutrient chemistry laboratory and specialized sampling apparatus for the 1974 and 1975 field seasons. Nine cruises were completed during 1973, eleven in 1974 and six in 1975 (Table 3). A total of 1,092 routine station visitations were made during the three-year study (Table 4).

Each of the limnological parameters that were monitored has its influence on the process of eutrophication. Correlation of biological data with the chemical and physical characteristics was formulated to assess the value of each parameter as an index of the trophic state of the lake (Table 5).

The biological parameters measured consist of: (1) planktonic and benthic organisms, (2) primary productivity, (3) chlorophyll, and (4) nitrogen-fixation and methane production by microbial organisms. The plankton segment of this study examined the distribution, types and quantity of phyto- and zooplankton. The predominance of any species or communities known to be associated with lake aging or marked changes in populations is used as a trophic index. Information derived from cell volume estimates, chlorophyll a measurements, and carbon-14 studies provides the basis for estimates of standing crops and primary productivity. Additional information on the status of the lake is supplied by benthic communities. These communities are relatively immobile and some members have relatively long life spans (as compared to plankton). Thus, benthic macroinvertebrate occurrence and density provide some measure of water quality over a prolonged period of time. In addition a measure of the trophic conditions of the lake can be calculated in terms of species diversity and changes in this diversity. Other biological indicators used in this assessment of abatement effectiveness are certain microbial forms and their activities. Analysis of biological nitrogen fixation has shown that forms capable of this activity are favored by environments in which nutrient input is significant. A similar biological activity closely associated with waters receiving nutrient inputs is the production of methane. Methane-producing bacteria are primary stabilizers of fresh organic matter desposited in sediments. The assessment of methane production in sediments gives an indication of loading of sediments with fresh, readily decomposable organic matter.

The chemical parameters considered are those involved as neces-

TABLE 3. LAKE ERIE CRUISE SCHEDULES FOR 1973-1975

Cruise	Year		
	1973	1974	1975
1	June 28 - July 12 (179-193)	April 7 - April 17 (097-107)	March 18 - March 31 (077-090)
2	July 17 - July 23 (198-204)	April 25 - May 4 (115-124)	June 9 - June 19 (160-170)
3	July 25 - August 2 (206-214)	May 14 - May 24 (134-144)	July 13 - July 24 (194-205)
4	August 7 - August 11 (219-223)	June 1 - June 10 (152-161)	August 27 - September 7 (239-250)
5	August 29 - September 4 (241-247)	June 28 - July 7 (179-188)	September 27 - October 6 (270-279)
6	September 19 - September 29 (262-272)	July 26 - August 4 (207-216)	December 4 - December 10 (338-344)
7	October 14 - October 24 (287-297)	August 12 - August 19 (224-231)	
8	November 7 - November 15 (311-319)	August 26 - September 7 (238-250)	
9	December 4 (338)	September 24 - September 27 (267-270)	
10		October 21 - November 1 (294-305)	
11		December 11 - December 14 (345-348)	

TABLE 4. STATIONS OCCUPIED IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE IN 1973-1975

Cruise / Station	1973									1974											1975					
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6
23	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
24		X		X	X	X	X	X		X	X	X	X		X	X	X		X		X	X	X	X	X	X
25		X	X	X	X	X	X	X		X	X		X	X	X	X	X		X		X	X	X	X	X	X
26		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	
27		X	X	X	X	X	X	X		X	X	X	X	X		X	X		X		X	X	X	X	X	X
28		X	X	X	X	X	X	X		X	X	X	X	X		X	X		X		X	X	X	X	X	X
29		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	
30		X	X	X	X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
31		X	X	X	X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
32		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
33		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X			X	X	X	X	X	X	X
34		X		X		X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
35		X		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
36		X		X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
37		X		X	X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
38		X		X	X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
39		X		X	X	X	X			X		X	X	X	X	X	X		X		X	X	X	X	X	
40	X	X			X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
41	X	X		X	X	X	X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
42	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	
43	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
44	X	X		X	X		X	X		X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
45	X	X	X	X	X	X	X	X		X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
46		X		X	X	X	X	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
47	X	X		X	X	X				X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
48	X	X		X	X		X			X	X		X	X	X	X	X		X		X	X	X	X	X	X
49	X	X		X	X		X			X	X	X	X	X	X	X	X		X		X	X	X	X	X	
50	X	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
51	X	X		X	X	X	X			X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
52	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
53	X	X		X	X	X	X	X		X	X	X	X	X		X	X		X	X	X	X	X	X	X	X
54	X	X	X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
55			X		X		X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	
56	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
57	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
58	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	
59	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
60	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
61	X		X		X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
65	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
66	X		X		X		X	X		X	X	X		X	X	X	X	X	X		X	X	X	X	X	
67	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
68	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
69	X		X		X	X		X		X	X	X	X	X	X	X	X	X	X			X	X			
70	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
71		X		X	X		X																			
72		X			X	X	X	X																		
73		X		X	X			X		X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
74		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
75	X		X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
76										X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	
77																										
78										X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
79										X	X	X	X	X	X	X	X		X		X	X	X	X	X	
81																			X			X	X	X	X	X
82																										
83																								X		X
84																					X					

TABLE 5. SYSTEM OF PARAMETERS USED TO INDEX THE STATE OF EUTROPHICATION IN LAKE ERIE

Physical Measurements

Temperature: measured on station at one-meter depth intervals ... exerts control on biological activities; identifies location of thermocline

pH: measured on station at various depths (one meter intervals)... affects biological activity; may reflect rate of photosynthesis

Conductivity: measured on station at various depths (one meter intervals)...a measure of dissolved material that will conduct an electrical current

Light Penetration: measured on selected stations at various depths (one-meter intervals)...energy source for conversion of inorganic materials into the biomass

Transmissibility: measured on station at various depths (one-meter intervals)... an indicator of concentration of suspended solids

Wind Direction & Velocity, Estimate of Wave Height and Period: measured on station...important factors in mixing of lake water

Water Chemistry

Dissolved Oxygen: measured on station at various depths (one-meter intervals) ...depletion of oxygen, particularly in the hypolimnion beneath the thermocline, limits higher life forms

Alkalinity: water sampled on station, analyzed underway...buffer to control pH; a measure of calcium bicarbonate in lake (an alternative nutrient for algae)

Soluble Reactive Phosphorus: water sampled on station; analyzed underway; phosphorus is currently considered to be primary cause of eutrophication as a nutrient of phytoplankton

Total Phosphorus: water sampled on station; analyzed on board, in port

Ammonia: water sampled on station; analyzed underway...indicator of nitrogen concentration, breaks down to nitrate/nitrite, indicator of relatively recent pollution

Nitrate/Nitrite: water sampled on station; analyzed underway...nitrogen is a primary nutrient for phytoplankton

Particulate, organic, nitrogen and carbon: water sampled on station, analyzed in Columbus...ratio of the parameters indicative of nutritional potential of the lake

(continued)

TABLE 5 (continued)

Biological Parameters

Benthos: sampled on station, analyzed on mainland...particular groups of midges withstand different eutrophic conditions; the particular groups present, and their relative abundance may indicate state of eutrophication

Plankton: sampled on station, analyzed on mainland...species of phyto- and zoo plankton present, and their relative abundance may also indicate state of eutrophication

Primary Productivity: water sample (containing phytoplankton) obtained on station, $NaCO_3$ tagged with radioactive carbon added, sample incubated and cells filtered on shipboard, ^{14}C in cells counted on mainland...primary productivity is rate of incorporation of inorganic carbon into molecules of living cells (increase of biomass); another indicator of state of eutrophication

Microbial Activity (methane production & nitrogen fixation): water sampled on station, analyzed underway with gas chromatograph (some samples analyzed on mainland)...fixation of inorganic nitrogen into an organic form of primary productivity; methane is produced by bacterial action on decaying organic matter that has sunk to the bottom, its concentration may therefore be indicative of past plankton populations

Chlorophyll a, b, and c: Water sample obtained on station, analyzed on mainland by spectrophotometer...measurement of these pigments can provide insight into relative amount of standing crop of algae, results to be correlated with primary productivity study and phytoplankton study

Data Analysis and Display

Contouring of Lake Erie Water Quality Data by Computer Graphics: development of a computerized system which can accurately construct a large number of illustrations of water quality and biological data in a short period of time at a relatively small cost... in addition, the system computes the areal extent of the hypolimnion and anoxic zone, the volume of hypolimnion, mesolimnion and epilimnion, the total heat and dissolved oxygen content or the concentration of other substance in the thermal layers, and volume weighted averages of any of these parameters (a volume weighted average is an average of the values which is weighted according to the volume of water registering each value.

sary precursors to the growth of plant protoplasm. These compounds are all the organic elements, but particularly: (1) carbon, (2) oxygen, (3) nitrogen, and (4) phosphorus. In addition to nutrients, other controlling factors are those found in the physical category. The physical parameters measured are: (1) meteorological and lake state conditions, (2) light penetration, (3) transmissibility, (4) pH, (5) temperature, and (6) conductivity. These data were used to estimate the indirect effects on algal problems such as: vertical mixing, surface transfer coefficients, upwellings, and dispersal of blooms; and the direct effects: of light penetration (photosynthesis), temperature (community respiration), pH (state of chemical compounds and reactions) and conductivity (measure of dissolved ions). The forms of nutrients examined in the study are: (1) bicarbonate (alkalinity), (2) soluble reactive phosphorus, (3) total phosphorus, (4) nitrate + nitrite, (5) ammonia nitrogen (4 and 5 comprise total dissolved inorganic nitrogen), (6) particulate organic nitrogen, and (7) particulate organic carbon. The last two parameters give an estimate of the energy stored in the biomass. Of particular interest are the levels of nitrogen and phosphorus present. It is generally accepted that accelerated eutrophication and increasing nitrogen and phosphorus concentrations commonly proceed together, and that in Lake Erie phosphorus is the limiting factor in algal blooms, particularly in the central basin.

Detailed descriptions of field methods used in this study are contained in the "Procedures Manual" prepared by the Center for Lake Erie Area Research (1974) and submitted to the Grosse Ile Laboratory, USEPA as part of the 1973 Progress Report for Grant No. R-802543. In general, field procedures consisted of a series of cruises normally requiring about ten days each. The ships were positioned by compass and/or radar. A typical cruise track was accomplished by making north-south transects; each leg required a full day to complete. Stations were usually visited only during daylight hours. On station, a bathythermograph (BT) was used to determine the thermal structure of the lake. If the lake was stratified, samples were taken at four depths: (1) one meter below the surface, (2) one meter above the upper "knee" of the thermocline, (3) one meter below the lower "knee" of the thermocline and (4) one meter above the bottom. If the lake was unstratified, samples were only taken at three depths: (1) one meter below the surface, (2) mid-water and (3) one meter above the bottom. In shallow water, less than seven meters, only surface and bottom samples were taken (Figure 2). Water samples were taken with Niskin bottles in 1973 and with a submersible pump in 1974 and 1975. Samples to be used for biological studies were taken with Niskin bottles throughout the study because of the danger of mechanical damage to planktonic cells

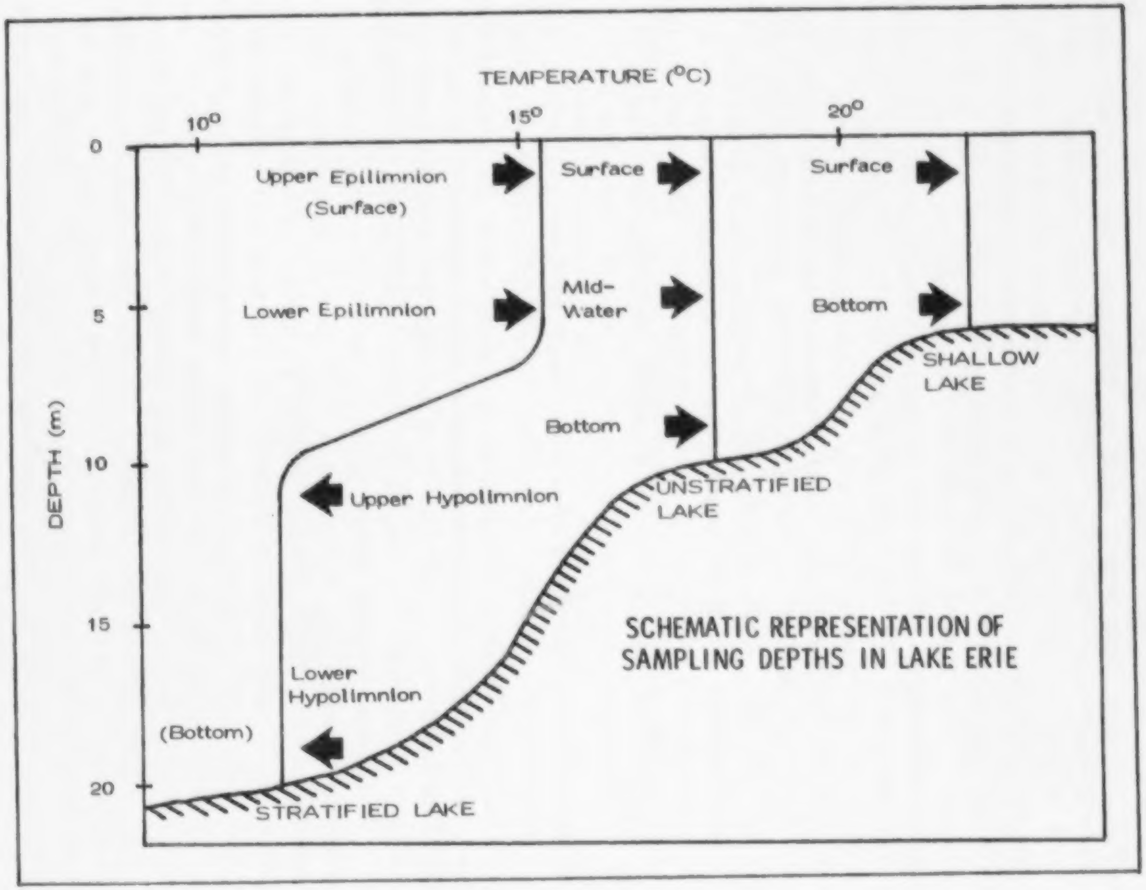

TEMPERATURE (°C)
10°
15°
20°
DEPTH (m)
0
5
10
15
20
Upper Epilimnion
(Surface)
Lower Epilimnion
Upper Hypolimnion
Lower
Hypolimnion
(Bottom)
STRATIFIED LAKE
Surface
Mid-
Water
Bottom
UNSTRATIFIED
LAKE
Surface
Bottom
SHALLOW
LAKE
SCHEMATIC REPRESENTATION OF
SAMPLING DEPTHS IN LAKE ERIE

Figure 2. Schematic representation of sampling depths in Lake Erie.

passing through the pump. The in situ measurements (shipboard sensors) were obtained by lowering submersible probes on a marked line and taking readings at one-meter intervals from surface to bottom.

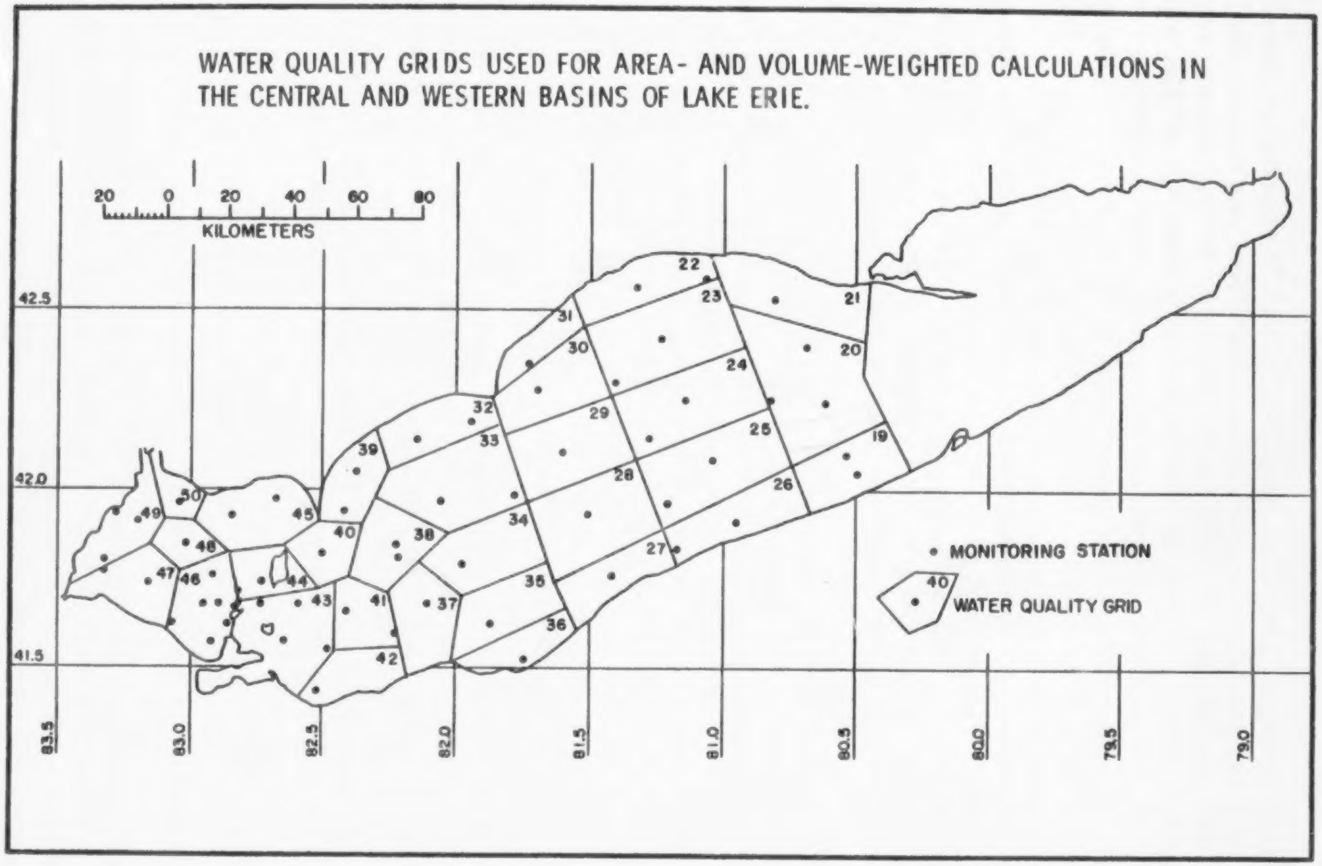
Laboratory methods are also detailed in the "Procedures Manual" produced by CLEAR (1974). Shipboard and mainland laboratory analyses followed the procedures in "Standard Methods" of the American Public Health Association (1971) or the methods developed by Technicon and CCIW for AutoAnalyzers, elemental analyzers, and spectrophotometers. Sedimentation techniques were used to concentrate phytoplankton from "whole water" samples. Enumeration of these samples was done with an inverted microscope. Zooplankton was sampled with vertical tows with 20-mesh (80 microns) nets fitted with inside and outside flowmeters. Identification was done with a dissecting microscope and a Ward counting chamber. Benthic macroinvertebrates were sampled with a Ponar dredge. Sediment was sieved through a 40-mesh screen and the retained organisms were identified with a dissecting microscope.

All of the water quality data from the 1973, 1974 and 1975 cruises have been computerized and placed in EPA's STORET data system. Dissolved and suspended substances data from lake samples have been analyzed by several techniques. Most of the parameters have been plotted on charts and contour maps constructed from these values. These maps provide a useful display of seasonal trends at various depth horizons in the two basins. Another technique involved determining the volume-weighted mean concentration or quantity of a particular parameter for the period of each cruise. To obtain these values the lake was subdivided into "water quality grids" (Figure 3) following methods developed for Project Hypo (Burns and Ross, 1972 and Burns, 1976). This procedure assumes that a particular station is representative of the polyhedron of surrounding water. The concentration determined for each station is extrapolated to total volume of water in the polyhedron. A summation of all of the polyhedrons within the basin will yield a total quantity of the parameter under consideration.

SIGNIFICANT TRENDS

Dissolved Oxygen

Dissolved oxygen (DO) concentrations in the western basin of Lake Erie for 1973 and 1974 were lowered to less than 6 ppm from June to September during periods of temporary stratification. In each of these years, over 50 percent of the basin experienced this condition.


WATER QUALITY GRIDS USED FOR AREA- AND VOLUME-WEIGHTED CALCULATIONS IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE.
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
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79.5
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• MONITORING STATION
40
WATER QUALITY GRID

Figure 3. Water quality grids used for area- and volume-weighted calculations in the central and western basins of Lake Erie.

In June and August 1973 the DO level in the mid and northeast sections of the basin was depleted to less than 1 ppm. Depletion was not as severe in 1974. The lowest concentrations were observed in Pigeon Bay (northeastern part of basin) during July and August where they did not fall below 3 ppm.

The central basin of Lake Erie, because of its middle latitude and moderate depth, stratifies into a relatively thick epilimnion (approximately 15-20 meters) and a thin hypolimnion (approximately 3-5 meters). The intervening mesolimnion (thermocline) has a distinct temperature gradient which limits mixing of dissolved substances between the other two layers. As early as 1929, Fish et al. (1960) observed oxygen deficiencies in the hypolimnion. Studies since that time (Carr, 1962; Beeton, 1963; Thomas, 1963; FWPCA, 1968 a & b; Herdendorf, 1970; Dobson and Gilbertson, 1971; Burns and Ross, 1972) have shown a persistent increase in magnitude of the deficiency and the area affected. Figure 4 illustrates the portion of the hypolimnion that has been so depleted of oxygen as to become anoxic (less than 0.50 ppm) for selected years between 1930 and 1974. These maps show a progressive growth in the anoxic area of the central basin from less than 2 percent in 1930 to nearly 70 percent in 1973. Trends in the anoxic area are given in Table 6. By 1973 over 93 percent of the hypolimnion had complete oxygen depletion. Because the time of maximum extend of hypolimnetic anoxia varies considerably due to meteorological conditions and because survey methods have improved through the years, these values should only be considered as estimates based on interpretations of historic data.

In 1974 the first depletion was observed shortly after stratification and was most severe in the southwestern section of the basin where the lake is less than 20 meters deep. By late July and early August concentrations of less than 2 ppm were observed throughout the north-central part of the basin. In early September nearly all of the central basin bottom water had less than 1 ppm. After three months of stratification, the lake cooled and overturned in mid-September resulting in dissolved oxygen levels above 6 ppm throughout the basin.

The level of DO in the eastern basin of Lake Erie did not suffer a serious depletion in 1973 or 1974. However, hypolimnion concentrations of less than 6 ppm were observed for each month during the period July to November, less than 5 ppm for August to October and less than 4 ppm in August 1974 and September 1973. In 1973 the greatest areal extent of low DO (< 6 ppm) occurred in mid-September and early October in the western and central sections

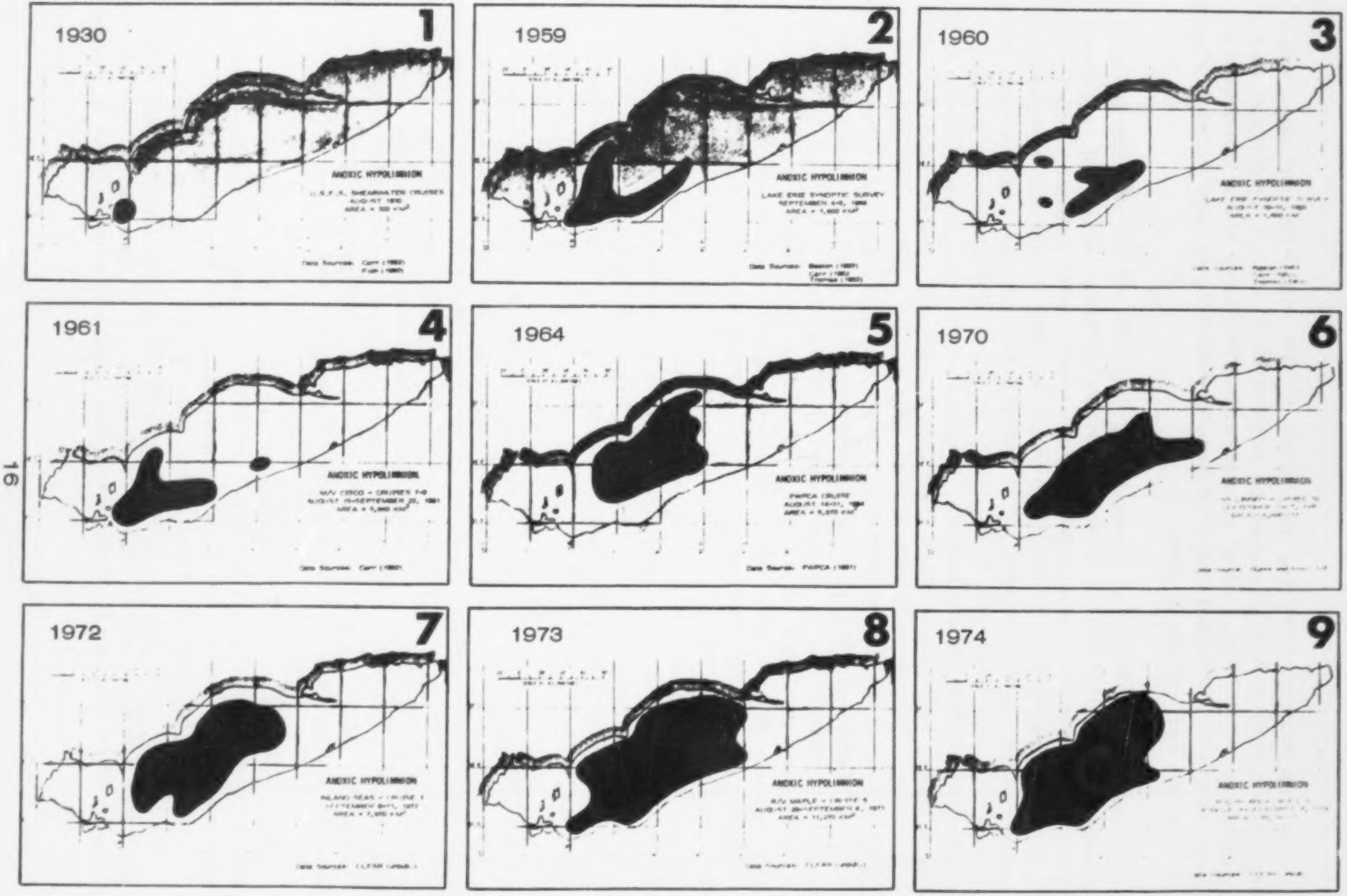

1930
1
ANOXIC HYPOLIMNION
1959
2
ANOXIC HYPOLIMNION
LAKE ERIE SYNOPTIC SURVEY
1960
3
ANOXIC HYPOLIMNION
1961
4
ANOXIC HYPOLIMNION
Data Source: Carr (1962)
1964
5
ANOXIC HYPOLIMNION
PWPCA CRUISE
Data Source: PWPCA (1961)
1970
6
ANOXIC HYPOLIMNION
1972
7
ANOXIC HYPOLIMNION
1973
8
ANOXIC HYPOLIMNION
1974
9
ANOXIC HYPOLIMNION

Figure 4. Trends in anoxic hypolimnion of Lake Erie 1930-1974.

TABLE 6. ESTIMATED AREA OF THE ANOXIC HYPOLIMNION OF THE CENTRAL BASIN OF LAKE ERIE 1930-1974

YEAR	AREA (km^2)	PERCENT OF CENTRAL BASIN	
		Hypolimnion	Total
1930	300	3.0	1.9
1959	3,600	33.0	22.3
1960	1,660	15.0	10.3
1961	3,640	33.0	22.5
1964	5,870	53.0	36.3
1967	7,500	68.0	46.4
1970	6,600	60.0	40.4
1972	7,970	72.5	49.3
1973	11,270	93.7	69.8
1974	10,250	87.0	63.4
1975	400	3.4	2.5

Data Sources:

1930 - Fish (1960)
1959-61 - Thomas (1963)
1964 - FWPCA (1968a)
1967 - Herdendorf (1970)
1970 - Burns and Ross (1972)
1972-75 - CLEAR

of the eastern basin. Whereas, in 1974 the greatest area of low levels (< 6 ppm) was found in the eastern half of the basin during mid-August and early September (Robert Sweeney, Great Lakes Laboratory, personal communication).

During thermal stratification in each basin the DO content of the hypolimnion experienced a marked decline. The oxygen deficit that takes place between thermocline formation is a rather complex set of mechanisms. The major components of these processes include:

1. Internal oxygen depletion within the hypolimnion due to bacterial oxidation of organic material and the oxidation of reduced metallic species (Burns and Ross, 1972), including oxygen consumption at the sediment water interface;

2. Volumetric changes in the hypolimnion caused by the loss or gain of water, including dissolved oxygen, to or from the overlying mesolimnion;

3. Exchange of water between the mesolimnion and hypolimnion including dissolved oxygen, without volumetric changes in either strata;

4. Entrainment of adjacent basin and tributary water masses within the hypolimnion, including dissolved oxygen.

Because stratification is so temporary in the western basin, adequate measurements of the oxygen deficit were not possible. Carr et al (1965), estimated that in 1963 only five days of stratification were required to reduce hypolimnion dissolved oxygen to 3 ppm in this basin, whereas, 28 days were needed in 1953. Near zero oxygen levels were observed in June 1973 after several days of calm weather which indicates that oxygen demand of the bottom sediments continues to be very high.

Trends in the net oxygen demand for the central and eastern basins are presented in Table 7. In the hypolimnion, the oxygen concentration in the central basin was reduced approximately 0.1 ppm per day in 1974; whereas, in the deeper eastern basin, the loss rate was only 0.01 ppm per day. This rate represents a doubling of the net oxygen demand since 1930 (Table 7). A slight reduction in the demand rate has been noted in the past five years which may be related to reduced pollution loads and high water conditions.

TABLE 7. TRENDS IN NET OXYGEN DEMAND OF THE CENTRAL AND EASTERN BASIN HYPOLIMNIONS OF LAKE ERIE

YEAR	NET OXYGEN DEMAND			
	Rate Per Unit Area ($mg\ O_2\ cm^{-2}\ day^{-1}$)		Rate Per Unit Volume ($mg\ O_2\ l^{-1}\ day^{-1}$)	
	Central Basin	Eastern Basin	Central Basin	Eastern Basin
1930	0.008	-	0.054	-
1940	0.015	-	0.067	-
1950	0.025	-	0.070	-
1960	0.037	-	0.093	-
1970	0.039	-	0.13	-
1973	0.053	0.023	0.12	0.012
1974	0.060	0.095	0.13	0.040
1975	0.067	0.076	0.10	0.040

Data Sources:

1930-70 - Dobson and Gilbertson (1971)
1973-75 - CLEAR and GLL

The anoxic conditions which now annually exist in the central basin have impaired the usefulness of the lake. Cold water fish, such as whitefish and lake herring, once over-summered in the cold bottom water. These species have been extirpated due to the lack of oxygen in the hypolimnion. Likewise, the diverse macroinvertebrate fauna of the bottom has been reduced to oligochaete worms and chironomid larvae. Upwelling of anoxic water at times causes discoloration of surface water along the Ontario shoreline and taste and odor problems in drinking water supply along the Ohio shoreline. A more subtle problem associated with anoxic conditions is the regeneration of nutrients, particularly soluble phosphorus. As the DO concentration approached zero (0.25 ppm), a sharp increase was observed in the level of soluble phosphorus; and at 0.10 ppm, DO regeneration of sedimented phosphorus resulted in levels over 10 times the normal background concentration for oxic conditions (Figures 5 and 6). This process provides a recycling of phosphorus in the lake system and may result in excessive algal production.

In 1975, a dramatic change in this situation appears to have taken place. Although a significant amount of oxygen depletion did occur, only a relatively small portion of the basin experienced complete anoxia (approximately 400 km^2). Equally important as the improvement in DO concentrations was the significant decline in regenerated phosphorus from the bottom sediments as a result of maintaining an oxic zone at the sediment/water interface throughout most of the basin (Tables 6 and 7).

The reason for this major shift in the oxygen regime of the hypolimnion is not immediately apparent. Reductions in nutrient loadings would be expected to produce a more gradual improvement, not the dramatic situation observed in a single year. An analysis of meteorological conditions and resultant water circulation phenomena provide some basis for an explanation.

Six cruises were conducted in the western and central basins of Lake Erie between March and December 1975. Dissolved oxygen concentrations were measured at one-meter intervals at 51 stations during each cruise. In March and April the lake was nearly isothermal and all DO levels were between 12-14 ppm. By mid-June the central basin had stratified and slight DO depressions were noted in Ohio waters north of Ashtabula and Huron. In mid-July this depression deepened on the American side of the lake, while the Canadian side continued to enjoy relatively high DO levels. At this time, an extensive area with less than 4 ppm DO persisted within a thin portion of the hypolimnion

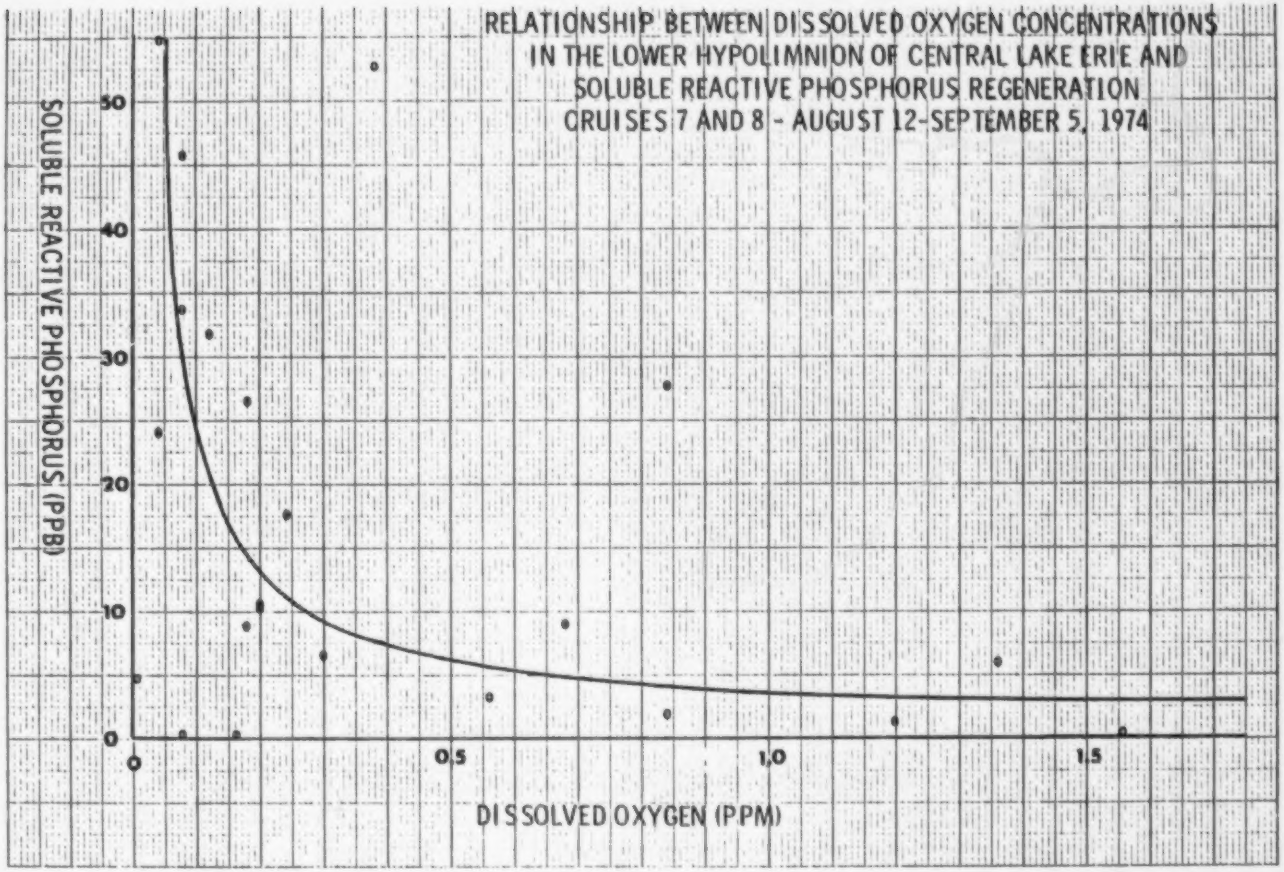


Figure 5. Relationship between dissolved oxygen concentrations in the lower hypolimnion of central Lake Erie and soluble reactive phosphorus regeneration, Cruises 7 and 8 - August 12-September 5, 1974.

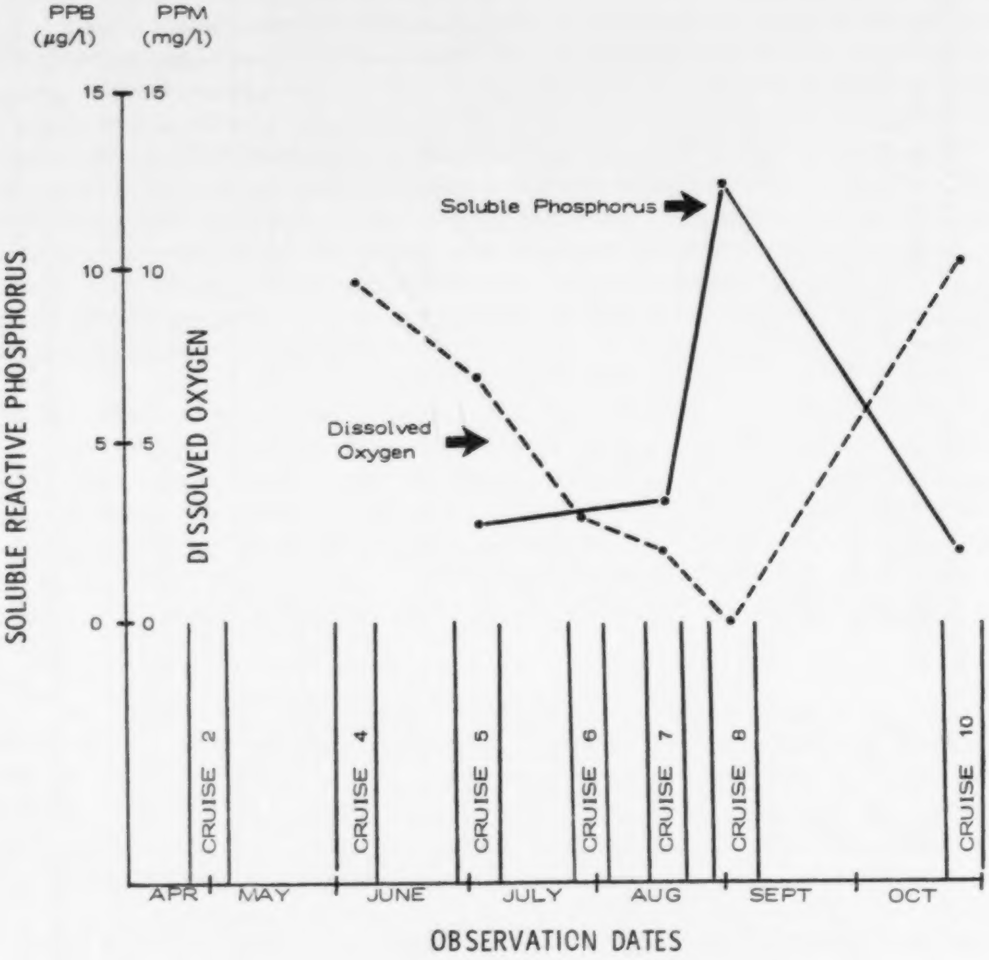


Figure 6. Concentration of soluble reactive phosphorus and dissolved oxygen in the central basin hypolimnion of Lake Erie - 1974.

off the Ohio shore. In late August and early September the maximum oxygen depletion occurred and resulted in the formation of an anoxic zone 50 km long and 8 km wide offshore between Cleveland and Huron, Ohio (Figure 7). At this time the zone of water with less than 4 ppm DO occupied a more central part of the lake, flanked by more oxygenated water east of Cleveland and on the Canadian side of the lake. The nearshore portions of the lake had overturned by late September and early October dissipating the anoxic zone and leaving only a small zone of oxygen depression near the center of the basin where the lake remained stratified. In December the lake was again nearly isothermal with high DO levels. No serious oxygen depression was noted in the western basin throughout the year with the exception of a small area southeast of the islands which experienced DO levels below 4 ppm in July.

Changes in the configuration of the hypolimnion during 1975 were similar to those of 1973 and 1974. The characteristics of the central basin hypolimnion for these years are compared in Table 8. The volumetric oxygen demand rates for all three years were similar with a slight decrease in 1975, whereas the area rate showed an increase in 1975. This is probably related to the increased thickness of the hypolimnion in 1975. With more water depleting at nearly the same volumetric rate, a higher depletion rate per unit area of the bottom would be expected. The increased thickness in 1975 apparently provided a larger reservoir of DO which was able to withstand the depletion rate without becoming completely anoxic.

Meteorological Conditions

A major change in the oxygen demand rate within the hypolimnion can be discounted as the reason for the improvement in the DO content of that layer. However, a comparison of hypolimnetic conditions for 1973, 1974 and 1975 provides some insight to this problem (Table 8). Compared with earlier years, from the onset the 1975 hypolimnion was thicker and contained a higher dissolved oxygen concentration. This situation persisted throughout the period of stratification. Apparently there was enough oxygen in the initial reservoir to satisfy the demand without depleting the hypolimnetic supply before the fall turnover replenished oxygen to the bottom.

The most plausible explanation for the thick hypolimnion involves the meteorological conditions at the time of thermocline formation. Monthly air temperatures and wind recording at Toledo, Ohio indicate that in 1973 and 1974 the warming from April to May was approximately

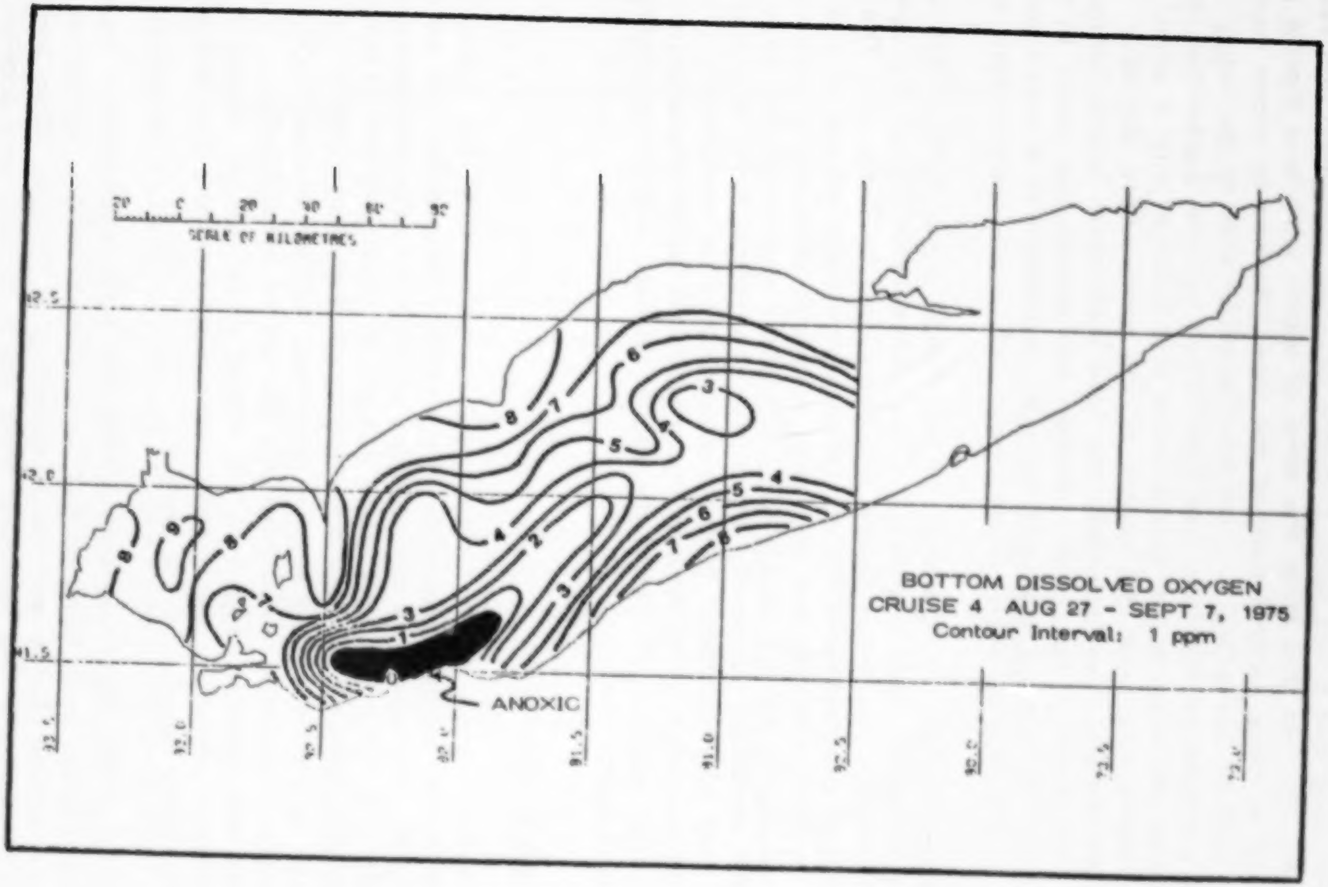

20 0 20 40 60 80
SCALE OF KILOMETRES
42.5
42.0
41.5
9
8
7
6
5
4
3
2
1
0
ANOXIC
BOTTOM DISSOLVED OXYGEN
CRUISE 4 AUG 27 - SEPT 7, 1975
Contour Interval: 1 ppm

Figure 7. Bottom dissolved oxygen, cruise 4, August 27-September 7, 1975.

TABLE 8. COMPARISON OF 1973, 1974 AND 1975 CHARACTERISTICS OF HYPOLIMNION IN CENTRAL LAKE ERIE

YEAR	JUNE			JULY			AUGUST			SEPTEMBER			NET OXYGEN DEMAND	
	Thick (m)	DO (ppm)	Temp (°C)	Thick (m)	DO (ppm)	Temp (°C)	Thick (m)	DO (ppm)	Temp (°C)	Thick (m)	DO (ppm)	Temp (°C)	loss/day (mg O_2/cm^2) Rate per unit area	loss/day (mg O_2/l) Rate per unit volume
1970 (Project Hypo)	-	-	-	-	-	-	-	-	-	-	-	-	0.039	0.13
1973	-	-	-	5.0	4.9	10.3	4.4	1.6	11.9	3.0	1.1	13.8	0.053	0.12
1974	6.2	9.9	8.8	4.6	5.2	11.8	4.3	2.1	13.5	-	-	-	0.060	0.13
1975	6.9	10.1	7.4	5.7	7.5	9.0	5.8	3.5	10.5	3.0	4.3	14.5	0.087	0.10

3.9°C, whereas in 1975 the air temperature increased 11.1°C during the same period. During the spring months the wind speeds were considerably lower in 1975 at Long Point, Ont. (Figure 8). It appears that a calm, rapidly warming spring can cause the thermocline to be fixed higher in the water column yielding a thicker hypolimnion. It was initially suspected that storms throughout the summer period resulted in the entrainment of warmer, oxygen-rich water from the upper layers. However, the warming of the hypolimnion was not significantly different in the three years under consideration, with the exception of September 1975 when it occurred in conjunction with the fall turnover, which has been discussed earlier. Average monthly wind speeds for June to September at Toledo were within one mile per hour for 1974 and 1975. This further substantiates the fact that increased entrainment did not occur as a result of unusual summer wind velocities in 1975.

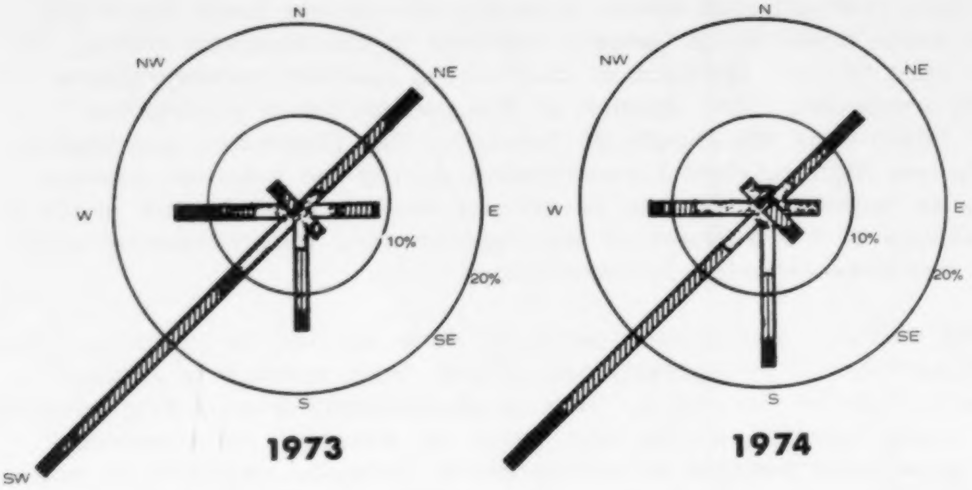
The present information leads to the conclusion that spring weather conditions can greatly influence the thermal structure of Lake Erie and thereby affect the degree of oxygen depletion which takes place in the central basin. A much more detailed inspection of meteorological data throughout the Lake Erie basin should be undertaken to verify these effects.

Nutrient Chemistry

The distribution patterns exhibited by all of the monitored nutrients were basically similar. Western basin concentrations nearly always exceeded those of the central basin. The western and southern nearshore areas of the western basin, specifically the vicinity of Monroe, Michigan and Toledo, Ohio, routinely exhibited the highest concentrations. This area is subject to the greatest loading from both municipal/industrial point sources and from land runoff non-point sources.

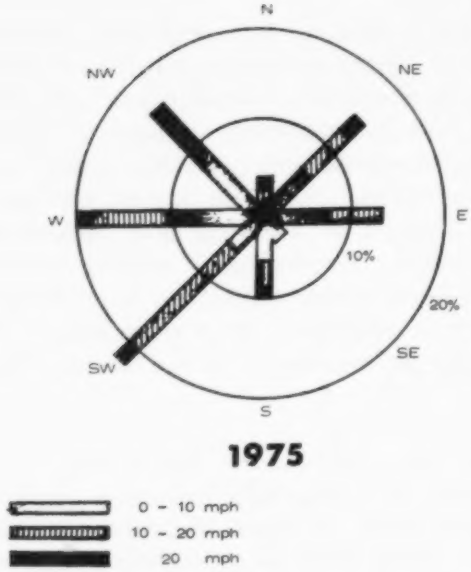
The Detroit River represents the most significant single source of nutrient loading to Lake Erie, largely because it contributes over 90 percent of the water input to the lake. However, the concentration of nutrients entering the lake is frequently lower than at those found within the basin; thus, distributional maps often show low contour values near the Detroit River mouth.

The central basin showed a somewhat similar pattern in that a distinct south to north gradient of decreasing concentration was evident for most nutrients. The Ohio nearshore region is subject to the highest



1973

WIND SPEED (MPH)	WIND DIRECTION (% time)							
	N	NE	E	SE	S	SW	W	NW
0–10	0.0	2.2	4.4	1.1	4.4	13.3	4.4	0.0
10–20	0.0	12.1	4.4	1.1	6.7	24.4	7.8	2.2
>20	0.0	4.4	0.0	0.0	2.2	2.2	1.1	1.1



1974

0–10	1.1	2.2	2.2	0.0	7.8	6.7	7.8	3.3
10–20	0.0	7.8	3.3	3.3	7.8	25.5	3.3	0.0
>20	0.0	4.4	0.0	1.1	2.2	8.9	1.1	0.0

1975

0–10	2.2	6.7	7.8	2.2	5.6	5.6	11.1	7.8
10–20	1.1	5.6	5.6	0.0	3.3	14.4	7.8	3.3
>20	0.0	2.2	0.0	0.0	1.1	2.2	1.1	4.4

Figure 8. Daily resultant wind at Long Point, Ontario for April, May and June 1973–1975.

loading in the central basin from both point and non-point sources. In addition, nutrient-rich water entering the central basin from the western basin tends to be largely confined to the southern shore. A distinct west to east gradient of decreasing nutrient concentrations was also observed. The section of the central basin joining the western basin near the mouth of Sandusky Bay (Sandusky sub-basin) typically has high nutrient concentration during the summer months. In early to mid-August anoxic conditions develop first in this shallow area because of the thinness of the hypolimnion, thus releasing sedimented nutrients (anoxic regeneration).

The vertical distribution patterns were similar for most nutrients. This western basin is typically isothermal from surface to bottom throughout most of the year. This is particularly true during periods of high winds (winter, spring and fall). In summer, calm periods permit ephemeral thermal stratification to develop, resulting in non-homogeneous vertical distribution of nutrients. The nutrients which are concentrated in the bottom waters due to bacterial decomposition and/or brief anoxic conditions in summer are quickly redistributed by wind and wave action in this shallow basin.

The central basin, like the western basin, is vertically homogeneous during non-stratified periods. For approximately 100 days from June to September the central basin is thermally stratified. At the onset of stratification the epilimnion and hypolimnion are very similar in chemical composition, however, as summer progresses these layers become increasingly dissimilar. In general, there is a net increase of nutrients in the hypolimnion as a result of settling and decomposition of plankton. In late August and early September, anoxic conditions prevailed in the hypolimnion. The change from oxidizing to reducing conditions in the hypolimnion resulted in release of phosphorus (concentrations of soluble reactive phosphorus increase up to twenty-fold), ammonia and silica.

Phosphorus budget. Nutrient budgets provide a basis for quantitatively assessing the net transfer of materials between various compartments of Lake Erie. Measurements of total phosphorus during the period 1970-75 (Figures 9 and 10) were used to calculate budgets for the western and central basins of Lake Erie (Table 9). Although the external loading of phosphorus to these basins has decreased slightly during this period (12%-western basin; 13%-central basin), the quantity and concentration of phosphorus have remained more stable (slight rise in the western basin and slight decrease in the central basin). Approximately 82 percent of the combined external loading was retained within the basins in the form of sedimented phosphorus. The western and central basin thereby serve as effective sinks for phosphorus.

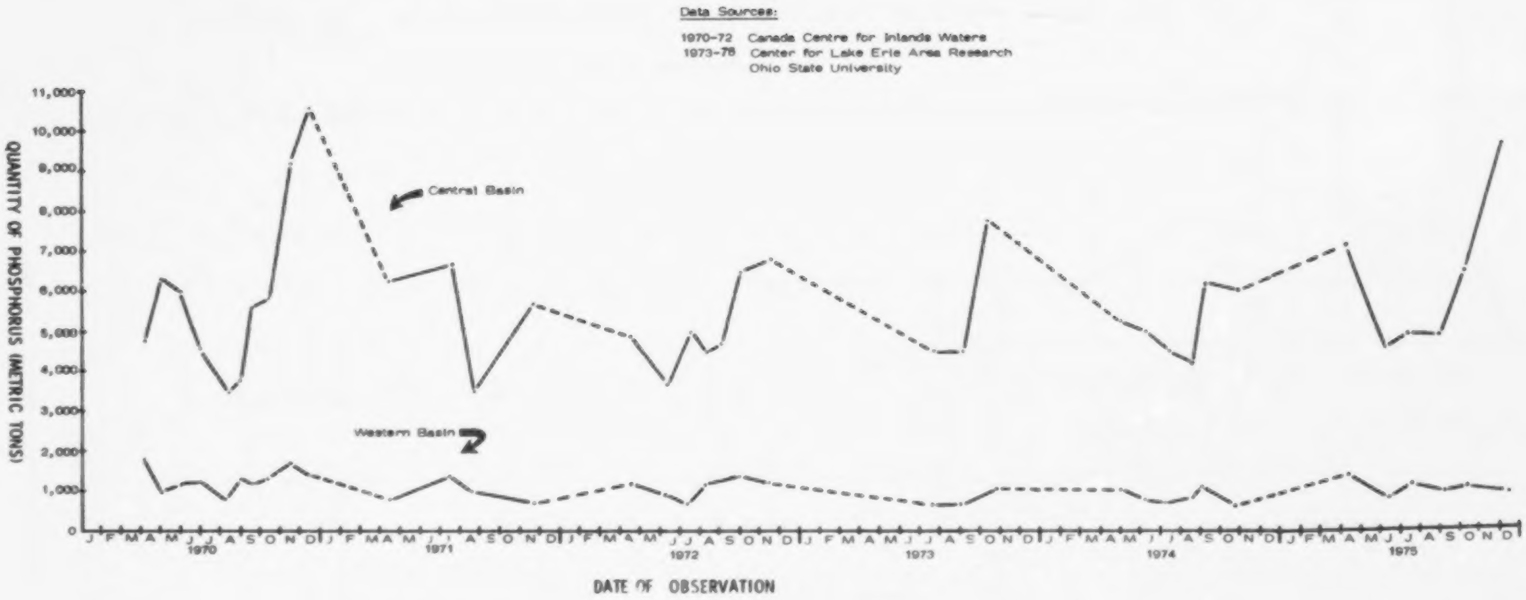


Figure 9. Quantity of phosphorus in Lake Erie, 1970-1975.

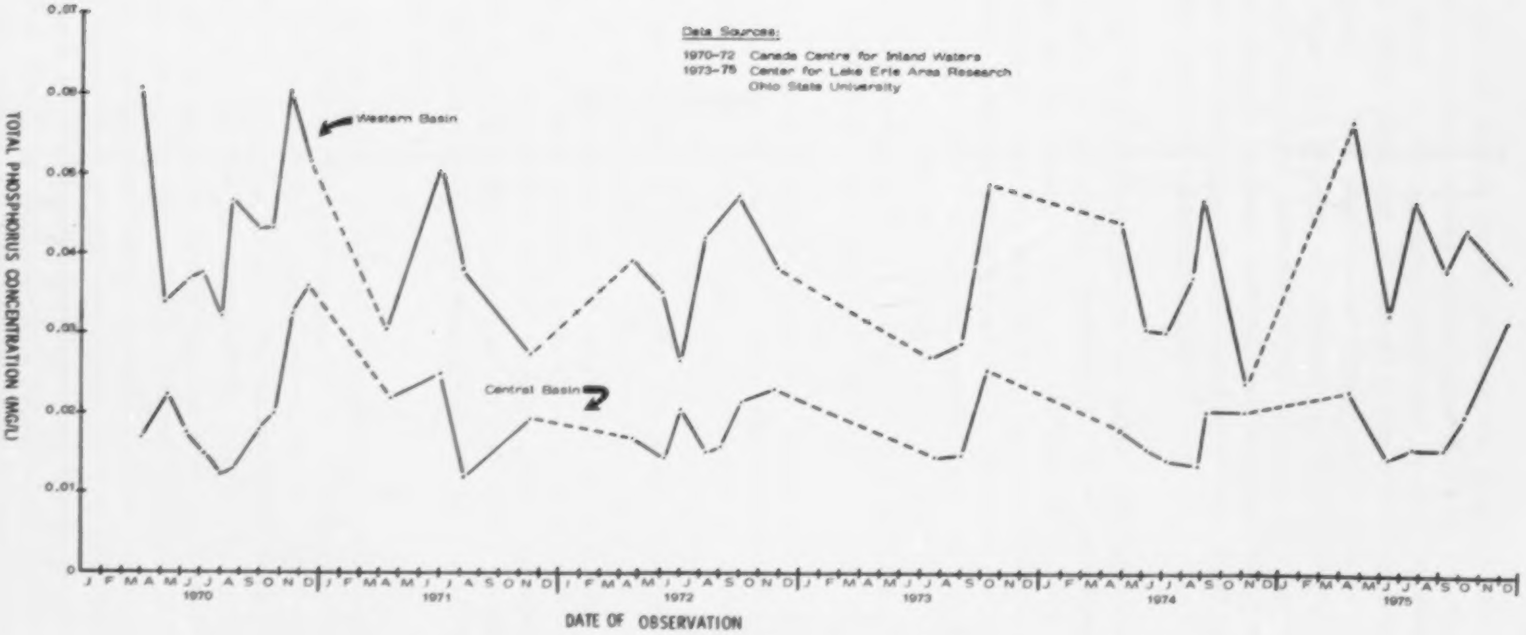


Figure 10. Total phosphorus concentrations in Lake Erie, 1970–1975.

TABLE 9. PHOSPHORUS BUDGET FOR THE WESTERN AND CENTRAL BASINS OF LAKE ERIE, MAY-SEPTEMBER 1970-1975

Year	WESTERN BASIN			
	External Loading (m tons per year)	Mean Quantity (m tons)	Mean Concentration (µg/l)	Retained Loading (%)
1970	17,000	900	38.3	61
1973	17,500	810*	34.6*	62*
1974	16,600	840	35.4	59
1975	14,900	980	41.8	53

Year	CENTRAL BASIN					
	External Loading (m tons)	W.B. Loading (m tons)	Mean Quantity (m tons)	Mean Conc. (µg/l)	Retained Loading (%)	Anoxic Regeneration (m tons)
1970	4,500	6,600	5,500	17.9	69	1900
1973	4,000	6,650	5,450*	17.5*	71*	2570
1974	4,200	6,800	5,250	16.6	67	1720
1975	3,900	7,000	5,150	17.0	63	730

* Estimated from partial data

Data Sources:

1970 - CCIW   1973-75 - CLEAR   External loading-U.S. Army, Corps of Engineers

The area of anoxia varied greatly during the study period; however, the quantities of total phosphorus in the central basin were not significantly different. For 1973, 1974 and 1975 anoxic regeneration in the western and central basins amounted to only 13.5, 8.2 and 4.0 percent of the combined external loading, respectively. The small percentage for 1975 (730 metric tons) is in response to the small area of anoxia observed that year. However, the central basin phosphorus budget for 1975 (Table 10) shows that 8 percent of the total phosphorus loading (internal plus external) is attributed to anoxic regeneration and 30 percent to oxic or physical regeneration (sediment resuspension). Physical regeneration, generally associated with winter and spring storms, appears to be the major source of internal phosphorus loading, whereas anoxic regeneration may be considered of secondary importance except for a short period of time in late summer.

Total phosphorus (TP). This parameter is considered useful in identifying areas of high nutrient concentrations and biological production. As with other nutrients monitored, some distinct distribution patterns were evident. Areas of high phosphorus loading generally produce productive regions where the nutrient-rich tributary waters mix with the lake. This situation existed along the western and southern shores of the central basin from Sandusky to Ashtabula Harbor. A decreasing west to east concentration gradient was found to be evident for TP and many other parameters monitored. Three major zones of decreasing concentrations could be distinguished: (1) western basin having the highest concentration, (2) western central basin, extending east from a north-south line between Rondeau Harbor to just west of Cleveland having intermediate concentration and (3) eastern central basin, extending eastward to the division between the central and the eastern basin having the lowest concentration.

The yearly variation in quantities of TP in the western basin were not nearly as great as the fluctuations in the central basin due to the relatively smaller volume of the western basin (Figures 11 and 12). The concentrations of TP in the western basin fluctuate greatly throughout the year. Initial spring concentrations are high as a result of loading from the tributaries entering the western basin, the vernal diatom pulse and resuspended sediments. The spring high was followed by a decrease during the early summer. This is due to a reduction in loading and settling of previously resuspended sediments. During the summer the concentration can fluctuate rapidly due to high winds resuspending sediments or the development of anoxic conditions. In 1974 anoxic conditions did develop in late August resulting in an increase

TABLE 10. CONCENTRATION AND QUANTITY OF TOTAL PHOSPHORUS IN WESTERN AND CENTRAL LAKE ERIE - 1975

Basin	Concentration ($\mu g/l$)	Quantity (metric tons)	Lake Volume (km^2)
Cruise No. 1 (March 27 - April 25)			
Western	56.61	1338.33	23.64
Central	23.00	7100.86	308.79
Cruise No. 2 (June 6-19)			
Western	32.35	760.15	23.50
Central			
Epilimnion	13.91	2421.42	174.03
Mesolimnion	15.66	469.27	29.96
Hypolimnion	15.65	1638.34	104.70
Total Basin	14.63	4529.03	309.49
Cruise No. 3 (July 13-21)			
Western	46.48	1085.42	23.35
Central			
Epilimnion	12.73	2325.01	182.64
Mesolimnion	17.85	634.71	35.56
Hypolimnion	21.19	1917.11	90.49
Total Basin	15.80	4876.83	308.69
Cruise No. 4 (August 30 - September 5)			
Western	38.24	892.88	23.35
Central			
Epilimnion	15.34	3488.53	227.39
Mesolimnion	14.17	215.86	15.23
Hypolimnion	17.91	1183.63	66.07
Total Basin	15.83	4888.02	308.69
Cruise No. 5 (September 9 - October 6)			
Western	43.24	997.44	23.07
Central	19.98	6134.24	307.06
Cruise No. 6. (December 2-14)			
Western	37.04	834.90	22.54
Central	31.66	9623.04	303.96

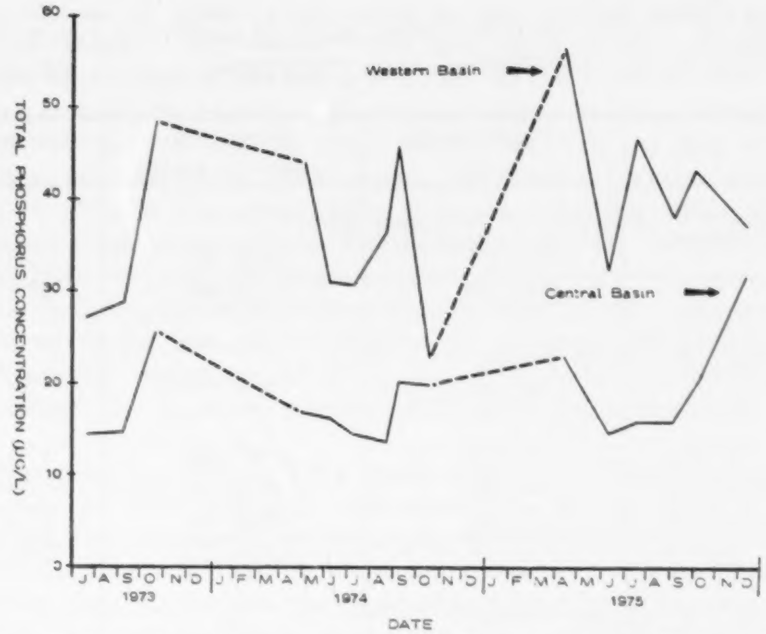


Figure 11. Total phosphorus concentration in Lake Erie, 1973–1975.

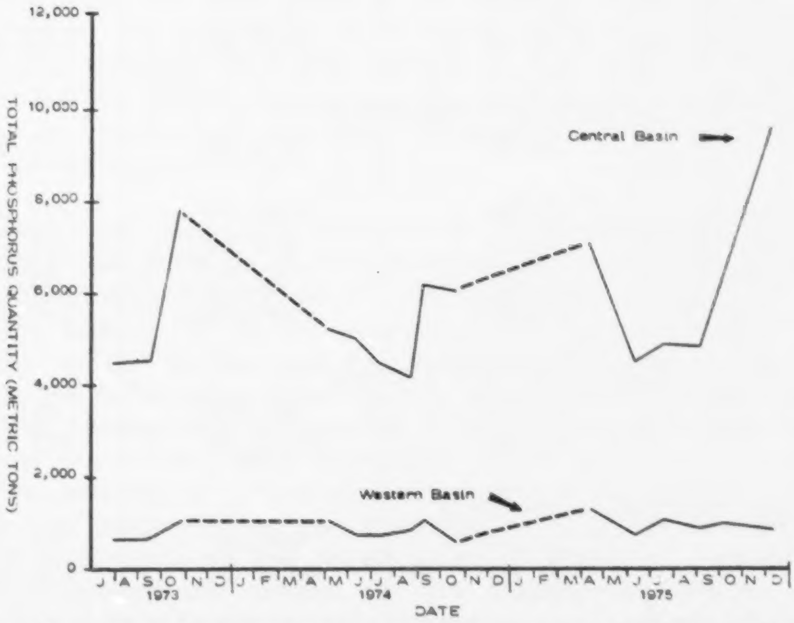


Figure 12. Total phosphorus quantity in Lake Erie, 1973–1975.

in phosphorus. A peak in TP also occurred in July 1975, following a period of high winds. Autumn was a period of increased quantities of phosphorus in the central basin; however, the western basin levels decreased both in quantity and quality compared with spring values.

Spring concentrations and total tons of TP in the central basin were high throughout the lake. This was due to the resuspension of previously settled inorganic and organic sediment and the high concentrations and quantities of phosphorus contributed by the tributaries. During the nonstratified periods of the season, seston-bound phosphorus contributed a large portion to the TP. Following stratification in late May or early June, much of the resuspended materials from the sediments settled. In the central basin the vernal phytoplankton pulse ceased and the cells continued to settle through the early summer; consequently, surface TP was reduced while hypolimnion concentrations increased. The TP continued to decrease until August when phytoplankton growth increased in the central basin. Surface values of TP increased during the late summer, possibly influenced by four sources: (1) nutrient-rich hypolimnion water mixed with the epilimnion, (2) western basin inputs into the epilimnion of the central basin, (3) point and non-point sources primarily along the southern shore and (4) sediment regeneration of TP in unstratified water of the central basin.

Bottom waters of the central basin during 1973 and 1974 greatly increased in concentration of TP during August. This was due to extensive anoxic hypolimnion regeneration of soluble reactive phosphorus (SRP) in the central basin. During 1975 no large increase of TP was found in the hypolimnion coinciding with limited development of anoxia in the basin. Following turnover in 1974, TP remained constant. The period after turnover was not greatly affected by resuspension of bottom materials, and TP values remained constant. The 1973 and 1975 post-turnover cruises demonstrated a different trend. Only a small increase occurred just following turnover in 1975, but by December the quantity of TP had nearly doubled (Figure 13). This dramatic increase may be attributed to large quantities of resuspended organic and inorganic sedimented materials during the late fall.

Soluble reactive phosphorus (SRP). Trends in the 1974-1975 quantities and concentrations of SRP in the western and central basin of Lake Erie are depicted in Figures 14 and 15. The western basin quantities of SRP were relatively stable during this period compared to the central basin; however, the concentrations varied more widely. Spring concentrations in the western basin remained high due to the extensive loading from the tributaries during that time of year. Following the reduction in flow from the rivers entering the western basin,

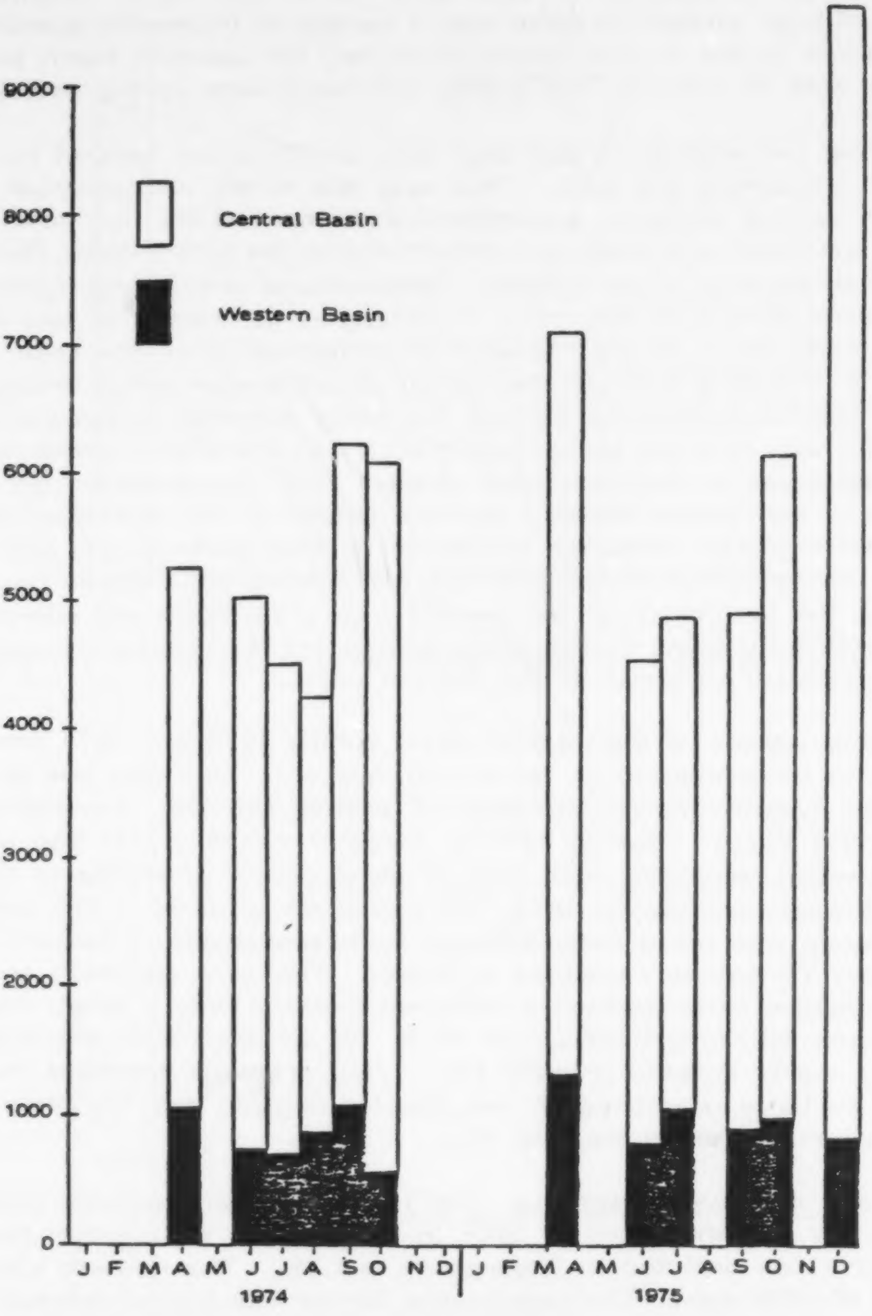


Figure 13. Volume weighted quantity (metric tons) of total phosphorus in Lake Erie, 1974-1975.

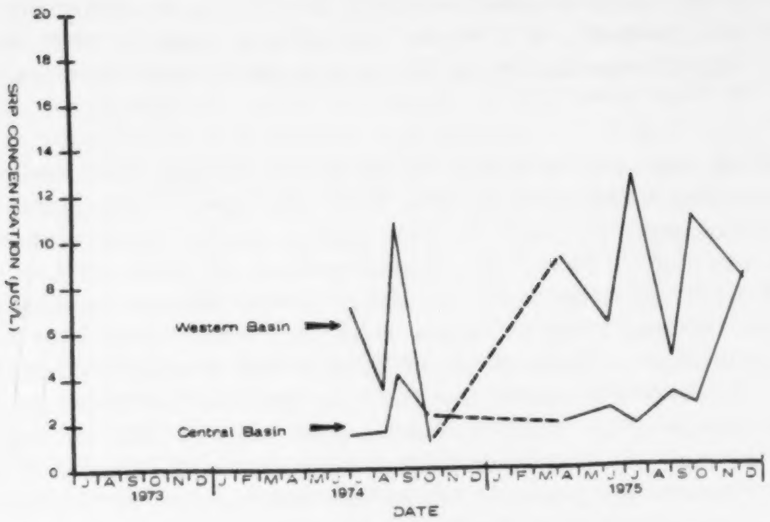


Figure 14. Soluble reactive phosphorus concentrations in Lake Erie, 1974–1975.

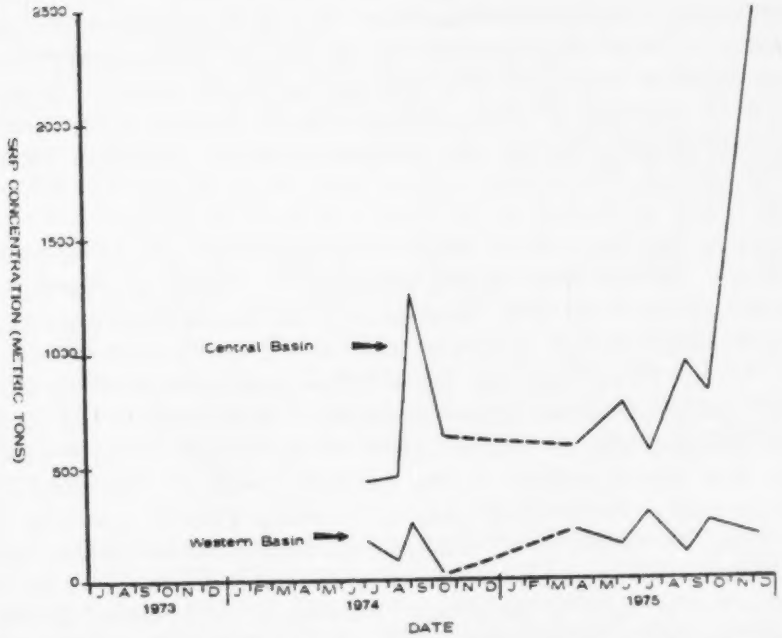


Figure 15. Soluble reactive phosphorus quantity in Lake Erie, 1974–1975.

the fluctuations in concentrations are largely due to internal processes. Large decreases in SRP are generally associated with an increase in chlorophyll a and vice versa. Anoxic conditions do exist in the western basin for short periods, and as in the central basin, SRP is released under these conditions adding to the extreme fluctuations that occur in the basin.

Following the spring pulse of phytoplankton in the central basin, the SRP increased and through the later portion of the summer there was an accumulation of SRP in the central basin hypolimnion water. During this period in 1974, the concentration of SRP in the hypolimnion increased from 3 µg/l to over 15 µg/l, while the tonnage went from less than 200 metric tons (mt) to more than 700 mt. This increase can be attributed to anoxic regeneration of SRP from the sediments in the central basin. During the same period a slight increase of SRP in the surface waters occurred. This increase was largely due to the exchange of phosphorus rich hypolimnion water into the epilimnion. Following turnover phytoplankton growth increased and uptake of SRP increased. This, as well as settling of plankton and inorganically bound SRP, accounted for the fall depletion. In 1975 the greatest change occurred in the late fall when the concentration in the central basin increased from 2.5 µg/l to greater than 8 µg/l and the tonnage increased from 800 mt to 2500 mt. This increase was substantially greater than the increase in 1974, which was attributed to anoxic regeneration. During ice-free conditions in the late fall and winter, the lake is subject to periods of high winds which readily resuspend bottom sediments. This turbulent action released large quantities of SRP from the sediments and interstitial water.

Nitrate plus nitrite. The highest concentrations of nitrate plus nitrite were found during the spring cruises. Vertical distribution was essentially uniform in both basins. The concentrations along the south shore indicated major sources of river inputs both in the western and central basins. The Detroit River flow was characterized by lower concentrations than the other river mouths. The entire north shore and mid-lake concentrations were significantly lower than those of the western basin and south shore of the central basin. By June, concentrations were greatly diminished due to a reduction of loading from the tributaries. The same general pattern as found in the early spring prevailed with the highest concentrations found along the south shore in both the western and central basins. Mid-lake and north shore concentrations were distinctly lower than those of the south shore. During July a slight decrease was evident in the western basin probably due to algal uptake. Distinctly higher concentrations were found near the western basin shorelines, primarily near the mouth of the Maumee

River. The south shore of the central basin remained higher than the mid-lake or north shore, and a slight increase in hypolimnion concentrations became evident. During August, surface concentrations of nitrate plus nitrite were markedly reduced due to possible algal uptake and losses to sediments or hypolimnion waters. Hypolimnion concentrations increased in July; however, a decrease was evident in August. This was likely due to the conversion of nitrate and nitrite to ammonia during the development of anoxic conditions. Following turnover, concentrations were further depleted possibly due to biological uptake.

Ammonia. In spring, concentrations of ammonia were uniform throughout the water column. Highest concentrations were found in the western basin primarily to the west and south of Pelee Island. The central basin exhibited two distinct regions-the northern half containing relatively low concentrations and southern half containing relatively high concentrations. The high concentrations found in the western basin and southern central basin were primarily due to high river inputs during the spring and wind-resuspended bottom materials.

Summer ammonia concentrations at the surface were reduced appreciably in both basins. This period coincides with an increase of biological activity. Bottom concentrations were greater than surface concentrations in both basins as a result of decomposition of spring and summer plankton. Concentrations were highest near the Maumee Bay and the south shore of the central basin. During mid to late August bottom concentrations of ammonia remained high in both basins. Prior to anoxia, ammonia concentrations continued to increase in the hypolimnion of the central basin as a result of decomposition of phytoplankton settling from surface waters. Following anoxia, ammonia was thought to be liberated from interstitial water into the hypolimnion. Consequently, very high concentrations of ammonia were recorded in the anoxic regions. After turnover, surface concentrations in both basins were uniformly low. Chlorophyll a levels were high throughout the lake, thus the low ammonia values could be attributed to algal uptake. Bottom concentrations remained higher than surface concentrations through the early fall.

Total inorganic nitrogen. The seasonal trends and quantities of total dissolved inorganic nitrogen are similar to those of nitrate plus nitrite. Nitrate plus nitrite generally contributed 80 to 90 percent of the total inorganic nitrogen; thus, the fluctuations were essentially the same. Concentrations and tonnages were greatest in the spring. Spring western basin concentrations were nearly 2.5 times greater than those found in the central basin. The contribution of total inorganic nitrogen from the tributaries was highest in quantity as well as concentration during the late winter and early spring. The tributary contributions accounted for the high values recorded in both basins early in the year.

Concentrations and tonnages were reduced over the summer months. By the end of the summer, yearly values for each basin were reduced to nearly the same level. The quantities of nitrate and nitrite in the hypolimnion dropped during the first portion of the summer. The hypolimnion concentrations rose during mid-summer, but decreased at the height of anoxia. Conversion of nitrate to ammonia during this period may have accounted for a portion of the decrease.

Following turnover, nitrate plus nitrite continued to decrease. However, the December 1975 cruise showed an increase in the concentration of total dissolved inorganic nitrogen. The increase was particularly dramatic in the central basin where the quantity rose more than 1500 tons. This increase during late fall may be a result of nitrification and increased flow from the tributaries.

Soluble reactive silica (SRS). During early spring the western basin concentrations of SRS were the highest encountered. Concentrations were uniform from surface to bottom throughout most of the western basin. A pronounced decreasing concentration gradient was evident from the western part of the basin into the central basin. The highest concentrations encountered were found along the south shore near Maumee Bay. The central basin was nearly vertically and horizontally homogeneous at this time.

By May, western basin concentrations were greatly reduced as a result of the reduction of tributary loading. Other factors contributing to the reduction in the western basin were assimilation by diatoms, movement of the SRS-rich water mass into the central basin, and sedimentation in the western basin. From May to June, western basin concentrations increased threefold. This was most evident along the northern and southern shorelines. By June, concentrations had returned to levels encountered during April. High concentrations were found along the western shore near the Raisin River during this period.

Central basin concentrations increased during spring, particularly in the hypolimnion. Surface concentrations were lower than bottom concentrations due to diatom assimilation and net losses to the hypolimnion. The south shore exhibited the highest concentrations in the central basin. During the remainder of the stratified season the surface concentrations remained nearly stable, and the bottom concentrations increased steadily reaching the highest concentrations during August. In the southwest half of the central basin, primarily near the Cuyahoga River, the hypolimnion concentrations were higher than any other region within the basin.

Following turnover, concentrations again increased throughout the western basin and remained at the same concentration into December. The central basin became vertically homogeneous by late September with areas of low concentration in the northern and eastern sections of the basin.

Particulate organic carbon (POC) and nitrogen (PON). In spring, the vertical distribution of POC was nearly uniform throughout the western and central basins. Concentrations in the western basin were significantly greater than those observed in the central basin. This was due to loading and resuspension particularly in the shallow regions and the development of the phytoplankton community in the northern and western portion of the basin. The mid-portion of the central basin exhibited the lowest concentrations, while along the south shore significantly greater values were recorded corresponding to the areas of highest chlorophyll *a* concentrations in the central basin.

Concentrations in the western basin increased by June accompanied by an increase in chlorophyll *a*, principally in the western half of the basin. Mid-lake central basin surface concentrations decreased between cruises in late spring due to settling. After the onset of stratification in the central basin, resuspension of POC was only significant in unstratified areas.

Throughout the summer, POC concentrations remained high in the western basin as did the concentrations of chlorophyll *a*. An area of low concentration persisted in the western basin associated with the inflow of the Detroit River, while Maumee Bay and the associated south shore area had very high concentrations. Surface concentrations in the central basin increased as the summer progressed. Bottom concentrations and distributions were very similar to those of the surface. This trend was particularly evident in the western half of the central basin. A distinct gradient of decreasing concentrations from west to east was evident through the entire summer.

Following turnover, POC decreased in the western basin, most noticeably in the Maumee Bay region. The concentrations of chlorophyll *a* increased slightly basin-wide indicating a possible settling of detrital carbon. Particulate organic carbon concentrations in the central basin were highest during October, corresponding to the highest concentrations of chlorophyll a. As previously noted, a distinct west to east concentration trend was observed with the greatest central basin levels occurring in the transition area between the western and central basins. Since no stratification existed during this time, resuspended sediments would also have contributed to the increased POC levels.

Particulate organic carbon values generally reflect seasonal changes in biomass of a plankton community. This relationship, however, does not show good positive correlation during periods when bottom material becomes resuspended. During periods of nonstratification, spring, winter and fall in the central basin and any period of high winds in the western basin, resuspension of carbonaceous materials previously settled may result in high particulate organic carbon values. Particulate organic carbon concentrations recorded during times of high resuspension represent a combination of detrital carbonaceous material and living cells present in the water column.

Particulate organic nitrogen (PON) concentrations and distribution patterns were similar to those reported for POC during 1974 and 1975. Similar fluctuations occurred throughout the year, although the magnitude of PON was much less.

Ten-year trends. Table 11 shows ten-year trends for total and soluble reactive phosphorus and for total inorganic, nitrate plus nitrite and ammonia nitrogen. Both TP and SRP indicate improvements in all three basins with the greatest reduction in the western and the least in the eastern basin. With decreased loading from the Detroit River this type of cleansing pattern would be expected. However, CCIW/EPA data from Project Hypo in 1970 (Burns and Ross, 1972), when compared with 1973-1975 data from the present study, show no significant changes in open lake concentrations (Figures 9 and 10). Similar methodologies and statistical treatments were used for the 1970-1975 period, but these differed from those used in 1963-1965, which may explain the apparent improvement.

Chlorophyll

Chlorophyll, green plant pigments essential to photosynthesis, can be used as an indicator of the relative algal biomass in an aquatic system. An analysis of chlorophyll concentrations over a period of years may show long term trends in algal populations.

TABLE 11. TEN-YEAR COMPARISON OF MEAN WATER QUALITY IN LAKE ERIE

PARAMETER	PERIOD OF OBSERVATION				PERCENT OF 1963-64 QUANTITY PRESENT IN 1973-74
	1963 - 1965		1973 - 1975		
	mg/l	tons (M)	mg/l	tons (M)	
Total Phosphorus					
Western Basin	0 160	3,800	0.035	839	22.1%
Central Basin	0.065	20,000	0.017	5,207	26.0
Eastern Basin	0.060	9,100	0.030	4,554	50.0
Soluble Phosphorus					
Western Basin	0.032	700	0.005	130	18.6
Central Basin	0.010	3,000	0.002	706	23.5
Eastern Basin	0.010	1,500	0.005	759	50.6
Total Inorganic Nitrogen					
Western Basin	0.350	8,400	0.298	7,090	84.4
Central Basin	0.176	53,000	0.157	48,663	91.8
Eastern Basin	0.176	26,700	0.158	23,984	89.8
Nitrate-Nitrite Nitrogen					
Western Basin	0.124	2,900	0.274	6,532	225.2
Central Basin	0.090	27,000	0.143	44,416	164.5
Eastern Basin	0.090	13,600	0.084	12,751	93.8
Ammonia Nitrogen					
Western Basin	0.159	3,800	0.024	558	14.7
Central Basin	0.086	25,700	0.014	4,247	16.5
Eastern Basin	0.086	13,000	0.074	11,233	86.4

Data Sources:

1963-64 - Federal Water Pollution Control Administration
1973-75 - Center for Lake Erie Area Research
Great Lakes Laboratory

In 1967 the Federal Water Pollution Control Administration (1968b) conducted three cruises on Lake Erie during which chlorophyll *a* and *b* determinations were made on water samples from 30 stations. The mean annual concentration for the western, central and eastern basins was 23, 9 and 6 µg/l respectively.

Glooschenko et al. (1974) reported on chlorophyll determination from 10 Lake Erie cruises during the period April to December 1970. They found the highest mean chlorophyll *a* values (11 µg/l) occurred in the mid-western basin, with a second maximum (6 µg/l) in the eastern basin north of Erie, Pennsylvania. The southern shore of the central basin was also characterized by high values, particularly east of Cleveland, Ohio. The lowest yearly means were found in the eastern portion of the central basin and most of the eastern basin (3 µg/l).

Investigations by the Center for Lake Erie Area Research and the Great Lakes Laboratory showed a distinct gradient in chlorophyll *a* concentrations from the western basin to the eastern basin in 1973, similar to that found by Glooschenko et al. (1974). Basin values for the period July to October are given in Table 12. The central basin has been divided into a western and eastern half to demonstrate the marked gradient across this basin. The western half showed a definite transition zone due to the influence of large algal populations in the western basin, whereas the eastern half was similar to the eastern basin and contained the lowest chlorophyll *a* concentration in the lake during the summer.[1] Figure 16 presents a graph of chlorophyll *a* concentrations in the lake during the period June 1973 to March 1975 which demonstrates the relationship of the basins and the seasonal variations which occur each year in response to algal populations.

Trends in the chlorophyll concentration in Lake Erie surface water are shown in Figure 17. Although the 1967 data contains both chlorophyll *a* and *b*, a definite down trend in the western basin biomass is indicated when compared with the other two basins. This trend is consistent with other chemical and biological parameters which also show a major improvement in the western basin and lesser amounts of recovery for the other two basins. The improvement appears to be related to the reduction in nutrient loading from the Detroit River and other tributaries which enter the western basin. Therefore, the nearly three-year flushing rate of Lake Erie would be expected to slow the response to reduced nutrients in the down stream basins. If the present trend continues, increased recovery should be observed in both the central and western basins.

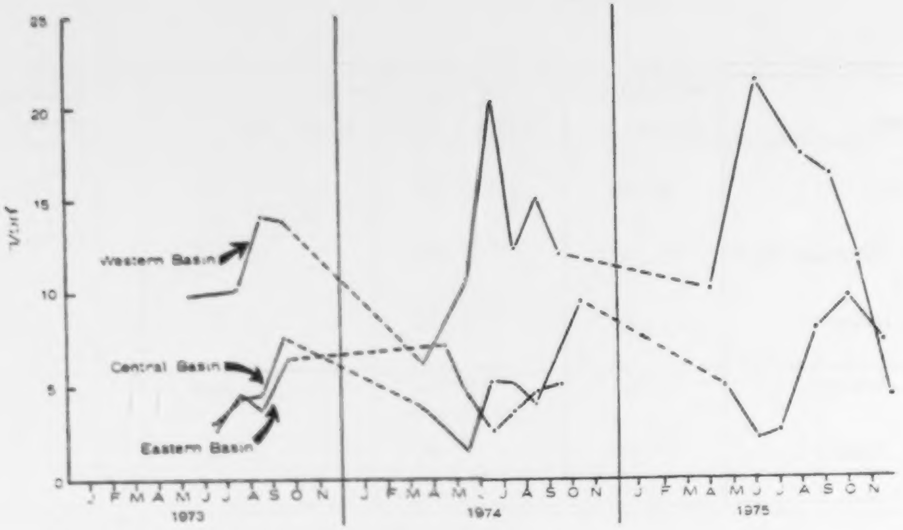
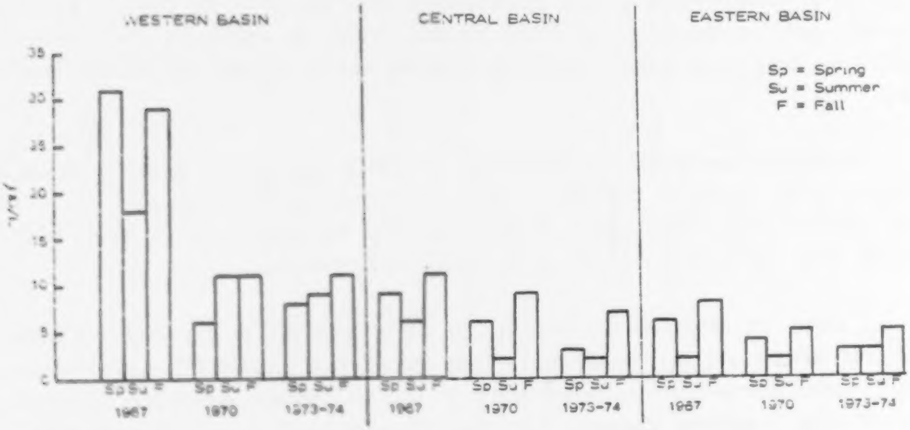


Figure 16. Concentration of chlorophyll a in Lake Erie surface water, 1973–1975.



Data Sources:

1967: Federal Water Pollution Control Admin. (1968a & b) – Chlorophyll reported as corrected a & b

1970: Canada Centre for Inland Waters – Chlorophyll reported as corrected a

1973-74: Center for Lake Erie Area Research and Great Lakes Laboratory – Chlorophyll reported as corrected a

Figure 17. Trends in Lake Erie surface water chlorophyll 1967–1974.

TABLE 12. AVERAGE SURFACE CHLOROPHYLL a IN LAKE ERIE - 1973 (UG/L)

Date	Western Basin	Central Basin		Eastern Basin
		West half	East half	
Mid-July	9.36	4.59	1.90	3.28
August-September	15.08	4.92	2.30	3.85
Mid-October	11.38	8.95	7.77	6.12
Annual Mean	11.94	6.15	3.99	4.42
Annual Ratio	2.70	1.46	0.90	1.00

During the period 1973-1975 chlorophyll a concentrations in the western and central basins of Lake Erie have increased (Figure 18). The peak summer concentration (volume weighted) in the western basin has risen from approximately 12 µg/l in 1973 to 21 µg/l in 1975. In the central basin the peak concentration occurs in fall. A similar increase was observed in this peak, from 8 µg/l in 1973 to 10 µg/l in 1975. Intermediate concentrations were found in both basins in 1974.

Volume weighted quantities of chlorophyll a also increased in the western and central basins from 1973 to 1975 (Figure 19). The central basin quantities increased significantly between 1974 and 1975 but the rise in the western basin was less pronounced.

Table 13 shows the ratio of chlorophyll a concentrations in the western and central basins. The western basin concentration during spring and summer is normally 2 to 10 times greater than the eastern part of the central basin. In fall there is less difference in the basin. The ratios between 1973 and 1975 reveal a trend toward a decreasing dominance of concentrations in the western basin, particularly in the fall. This is probably the result of a decrease in nutrient loads to the western basin via the Detroit River coupled with the regenerated nutrient added to the central basin after fall overturn.

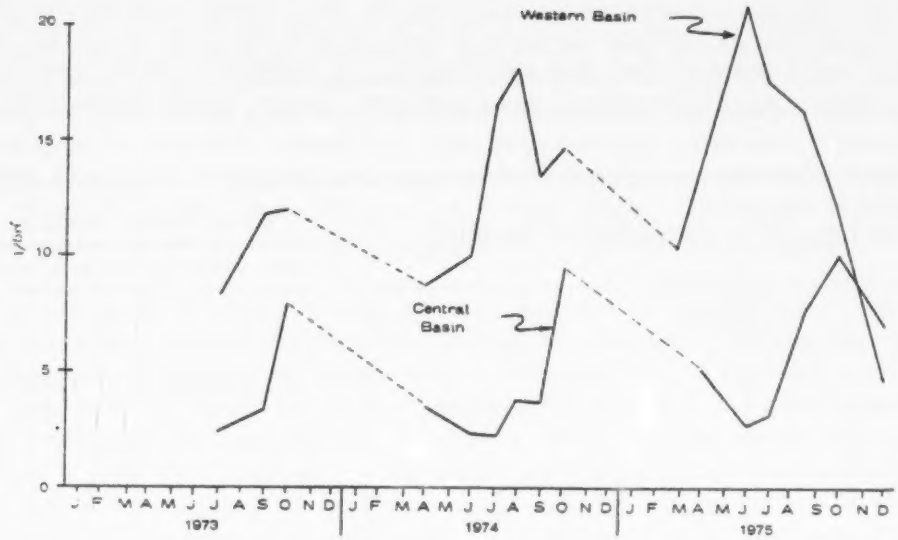


Figure 18. Volume weighted concentration (ug/l) of corrected chlorophyll a in Lake Erie 1973-1975.

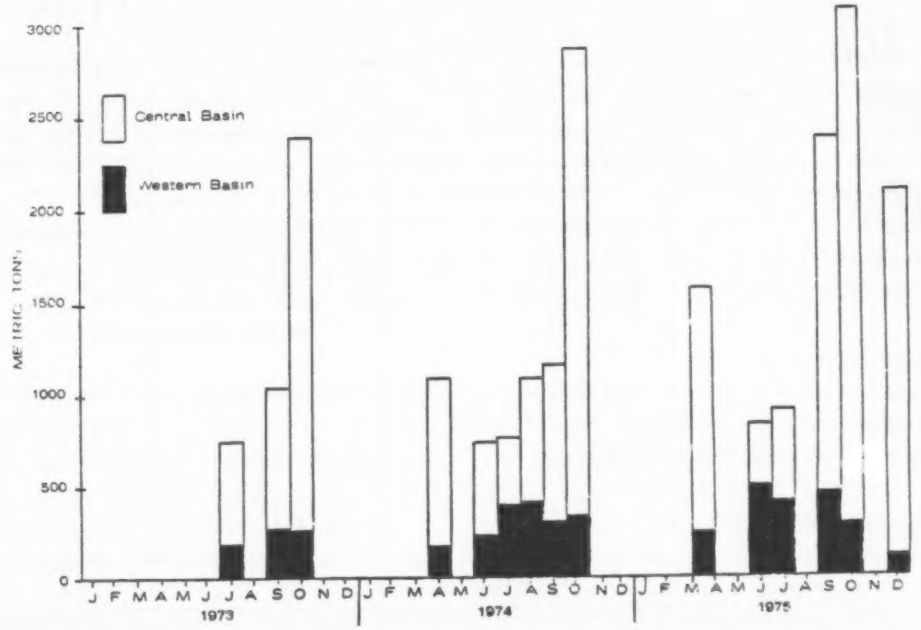


Figure 19. Volume weighted quantity (metric tons) of corrected chlorophyll a in Lake Erie 1973-1975.

TABLE 13. RATIO OF CHLOROPHYLL a CONCENTRATION IN WESTERN AND CENTRAL BASINS OF LAKE ERIE 1973-1975

DATE	WESTERN BASIN	CENTRAL BASIN	
		West Half	East Half
April			
1974	2.91	1.44	1.00
1975	2.33	1.41	1.00
June			
1974	3.95	0.80	1.00
1975	8.78	1.37	1.00
July			
1973	4.77	2.05	1.00
1974	9.82	2.23	1.00
1975	7.45	1.90	1.00
August			
1974	6.21	2.09	1.00
September			
1973	4.95	2.20	1.00
1974	4.75	1.92	1.00
1975	2.57	1.62	1.00
October			
1973	1.56	1.08	1.00
1974	1.89	1.62	1.00
1975	1.22	0.98	1.00
December			
1975	0.70	1.13	1.00

Microbial Activity

This microbial study was undertaken to monitor a select number of metabolic by-products of bacterial activities and to equate these parameters to the eutrophic processes occurring in Lake Erie. The monitoring of dissolved methane, sediment methane evolution and sediment methane production potentials was of primary interest. Secondly, an attempt was also made to estimate the contribution of biological nitrogen fixation to the nutrient budget of the lake. Nitrogen fixation potentials were estimated by the acetylene reduction technique.

The nitrogen fixation in the aquatic system is performed mainly by the blue-green algae and certain bacterial species (largely by Azotobacter and Clostridium species). The amount of fixation occurring in the water column or in the sediments may be a relatively sensitive indicator of loading, particularly when compared to dissolved methane in the water column and to methane production potentials in the sediment. For example, if the microbial cell is subjected to a high concentration of organic material that is rich in organic nitrogen, the cell in most cases will use the organic nitrogen. If, however, the external loading is rich solely in organic carbon, the microbial cell will be forced to use inorganic forms of nitrogen or will resort to nitrogen fixation.

Because of the ready reserve of dissolved inorganic nitrogen in the water column during the 1973-1975 cruises, no acetylene reduction potentials were observed during this survey. However, sediment values indicated maximum fixation potentials (3-6 nanomoles C_2H_4/g sediment per day) in the mid-portion of the western and central basins. The inshore regions and the eastern sector of the central basin had the lowest potentials. In general, the data tend to indicate that a sufficient quantity of fixed nitrogen, either organic or dissolved inorganic forms, is available in this ecosystem.

The methane data obtained during this investigation showed some interesting trends. In early spring a minimal quantity of methane was found throughout the water column. The concentration was less than 10 parts per billion (ppb), which is at the lower detection limit of the chromatographic system utilized. This low concentration was primarily due to the low temperature and well oxygenated conditions in the entire lake. A rapid increase of dissolved methane occurred during the late spring - early summer period of 1974. This period demonstrated consistent increases in methane concentrations and culminated in the yearly maximum during June. This maximum can be attributed to the warming of the water column, to the residual organic build up during the winter and to the increase in available organics caused by the spring diatom bloom. A number of geographic or basin effects are evident from methane concentration contours. The entrainment of colder eastern basin water into the central basin is demonstrated by low methane values in the bottom and particularly in the upper hypolimnion waters. The warmer surface and lower epilimnion waters are unaffected by the colder entrained water. The surface water of the mid-portion of the central basin possesses a uniform horizontal distribution of methane but there is evidence of two western basin effects. One is the low flux of methane observed entering from the western basin through Pelee Passage, the second is the significantly higher impulse recorded lakeward of Sandusky Bay. The colder hypolimnion water is not affected by the western basin water, but is significantly influenced by the previously mentioned eastern basin water.

The mid-summer cruises show a significant decrease in the concentration of dissolved methane. During the development of anoxia and at the time of maximum anoxia, the methane concentrations were surprisingly low. The annual fall turnover and post-turnover periods resulted in a twofold increase in the methane concentrations of the water column as compared to the late summer cruise. Of the two major western basin tributaries, Detroit and Maumee Rivers, only the bottom water of the Maumee made a significant direct contribution to methane to the western basin. A major difference between the methane concentration in the surface and bottom water indicates that the warmer western basin water was flowing up the Maumee River estuary, forcing the colder river water underneath. The western basin possesses a smooth linear gradient between the Detroit and the Maumee Rivers. Methane production observed along the south shore appears to be related to organic loading from the Detroit River. The mid-winter cruise represents a stabilization of the methanogenesis of the central basin. Sandusky Bay, Fairport and Ashtabula Harbors represent locales of obvious organic loading to the lake surface water. Unlike the nitrogen fixing potentials of the sediments the maximum values for methane production potentials (0.03-0.06 mg CH_4/g·day were observed in the nearshore sediments, particularly along the south shore in the vicinity of major tributaries. This potential appears to be a good indicator of organic loading. _In situ_ measurements in Cleveland Harbor (July 1975) yielded methane evolution rates in excess of 70 mg/m^2·hr. However, the overlying water column dissolved methane concentrations ranged from 10-45 ppb (methane solubility in water is approximately 20 ppm). Therefore the rate of methane oxidation is apparently very rapid. This rapid oxidation would result in a high oxygen demand in the harbor region.

Phytoplankton

Numerous investigations of phytoplankton populations in restricted bays, river-mouths and nearshore areas of Lake Erie have been undertaken in the past 50 years. Maumee and Sandusky Bays are highly productive, developing large phytoplankton populations, thus being a major source of biomass to the open lake. Except for the Detroit River with its relatively clear mid-channel flow, high densities of phytoplankton were found in the regions of mixing between turbid, nutrient-rich tributary waters and clear lake waters.

Of the three Lake Erie basins, the western basin has received the most extensive coverage. During 1929 and 1930, phytoplankton survey samples were taken at numerous stations in the western basin (Wright, 1955). By correlating phytoplankton composition and quantity in the island region to areas of tributary influence in the western basin, Wright concluded that the island region was richer in phytoplankton than either the central or eastern basins, Lake St. Clair, or the mouth of the Detroit River. However, the areas near major tributaries (Portage, Raisin and Maumee Rivers) were significantly more productive than the island region. This was attributed to the shallowness of these areas as well as to their being major areas of nutrient input. A seasonal pattern was observed including a spring pulse consisting almost exclusively of diatoms (Asterionella, Stephanodiscus, Melosira and Synedra comprised the major portion of the peak) with greens and blue-greens predominant through the summer and into the early fall. The blue-green pulse followed that of the greens and coincided with the autumn diatom peak. The taxa comprising the blue-green pulse were Coelosphaerium, Oscillitoria, Merismopedia and Gomphosphaeria. The only other taxon of importance was Microcystis which occurred during late September. The fall diatom pulse was comprised of the same taxa found during the vernal pulse, with the addition of Fragilaria.

Phytoplankton community studies undertaken during the late 1930's and early 1940's by Chandler (1940, 1944) showed that annual differences in phytoplankton populations were largely influenced by meteorological conditions. Turbidity caused by wind-induced bottom resuspension and the sediment load contributed by southern tributaries have a very pronounced effect on phytoplankton pulses. For each of the years, the seasonal composition of the standing crops was similar, but the magnitude of the group present varied. Diatoms were dominant in both the spring and autumn pulses; however, during the spring they comprised up to 90 percent of the total standing crop. The maximum spring pulse occurred as early as February and as late as May through the years 1939 to 1942. The vernal pulse was dominated by *Asterionella formosa* each year. The autumn pulse began during late July or early August and was comprised of diatoms, greens, and blue-greens. The greens and blue-greens together accounted for approximately 50 percent of the community, with the blue-greens comprising the greater portion. Unlike the spring pulse, the fall diatom pulse was co-dominated by several taxa, principally *Melosira*. During late fall and winter the diatoms again comprised greater than 80 percent of the algal population. The standing crop of phytoplankton peaked in the spring, declined during mid-summer, and peaked again during late summer continuing into early fall. The winter months exhibited low standing crops.

Britt et al. (1973) examined phytoplankton from six stations in the island region during the summers of 1961, 1962, and 1963. In comparing the percentage of composition of phytoplankton by taxonomic divisions, a pronounced increase in dominance of blue-greens was noted since 1929. *Microcystis* and *Aphanizomenon* were dominant during all three years. A change in the dominant species of diatoms also occurred. Hohn (1969) compared diatom data from several surveys from 1938 through 1965. He found the predictable spring and fall diatom pulses, but in addition, a summer high was also noted in the 1960's. By the spring of 1955, the actual intensity of the vernal pulse had increased by a factor of almost eight compared to that of the spring of 1939. Hohn found that the major taxa reported during the early 1940's were still present, but that their relative importance had changed significantly. Dominance had been assumed either by taxa not previously recorded or taxa which had only occasionally been observed. Verduin (1964) documented the change in dominant species composition (prior to 1950 to the period of 1960-61) in the western basin as a shift from *Asterionella formosa*, *Tabellaria fenestrata* and *Melosira ambiqua* to *Fragilaria capucina*, *Coscinodiscus radiatus*, and *Melosira binderana*. He attributed this change to increased nutrient loading from agricultural run-off.

During 1950 and 1951, Davis (1964) obtained samples from nine stations in and around Cleveland Harbor and found vernal and fall peaks similar to those occurring in the western basin. During the spring pulse diatoms constituted nearly 100 percent of the community while the greens and blue-greens were more important in the fall. Using data supplied by the water treatment facilities of Cleveland, he documented an increase of 443 cells/ml per year from 1927-1964 with a period of substantially greater increase (122 cells/ml per year) occurring between 1956-1964. The major dominant spring diatom changed from *Asterionella* to *Melosira* during the early 1950's, whereas the fall dominant shifted from *Melosira* to a mixed dominance of *Melosira*, *Fragilaria* and a number of blue-green species.

Samples obtained for the International Joint Commission in 1966 and 1967 from Canadian water intakes (one municipality in the western basin, two in the central basin, and three in the eastern basin, substantiated a decreasing west to east trend in numbers of plankters. The western basin had a high population of blue-greens during the summer and fall not found in the central basin or eastern basin stations. Diatoms remained the dominant plankton group in the spring, fall and winter in all basins, while during the summer the greens and blue-greens were predominant. In a similar study conducted by the Ohio Environmental Protection Agency, phytoplankton was examined at 10 intakes along the Ohio shoreline and showed similar seasonal trends and dominant groups from 1968 to 1972. This study also indicated a tentative decrease in total counts during this period.

The first basin-wide phytoplankton survey of the central basin was conducted by Burkholder (Fish, 1960) at 27 stations in June, July, August and September of 1929. Diatoms were the predominant group during each cruise except in August when all three groups were equally represented. Greens were present through the entire study but were most important during September. Blue-green populations were greatest during June with a smaller pulse occurring in September. Many species found to be common during the study are also commonly found in the lake during the 1970's. Not until 1963 through 1968, when the Federal Water Pollution Control Administration undertook surveillance programs, was the entire lake investigated. During both study periods, spring and fall pulses of diatoms occurred in both central and western basins with a decrease in algal density from west to east. Blue-green pulses occurred during the fall of 1963 and 1964 to a much greater extent than during the 1967 and 1968 period. The most thorough Lake Erie phytoplankton study to date has been by Munawar and Munawar (1976). Species composition and biomass values were determined for each basin from April through December of 1970. On the average, diatoms were found to comprise more than 50 percent of the phytoplankton in both the western and central basins, while the phytoflagellates were found to be of lesser importance. The blue-greens were most significant in the western basin, primarily in late summer.

From July 1973 through May 1974, 87 plankton samples (two per week) were collected with a Wisconsin plankton net (80-micron mesh) in Fisheries Bay (Station 77) of South Bass Island in western Lake Erie (Figures 20-23). The purpose of this special study was to develop

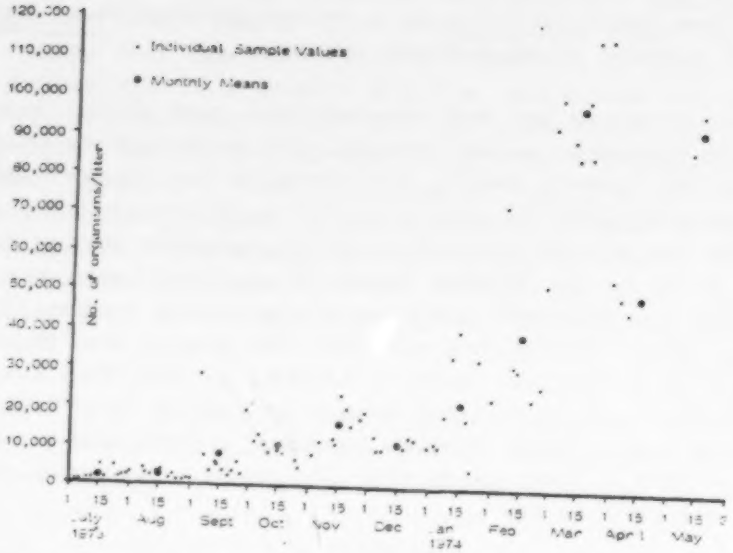


Figure 20. Total phytoplankton populations at Put-in-Bay.

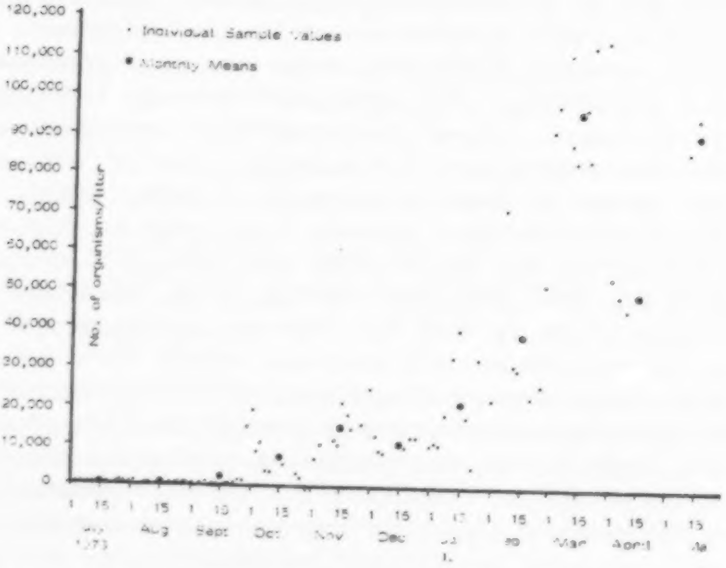


Figure 21. Total bacillariophycean populations at Put-in-Bay.

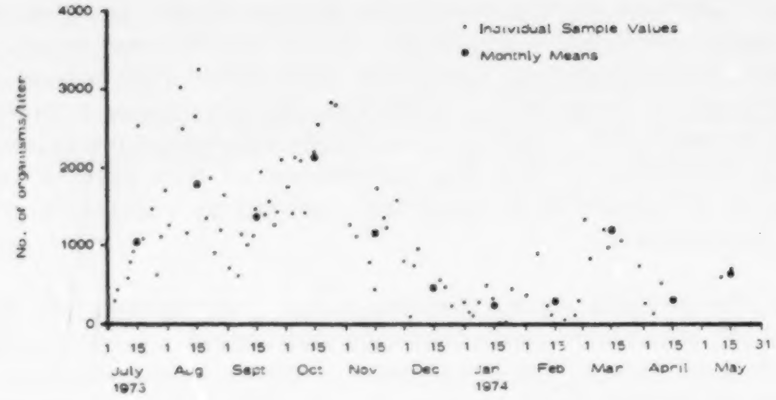


Figure 22. Chlorophycean populations at Put-in-Bay.

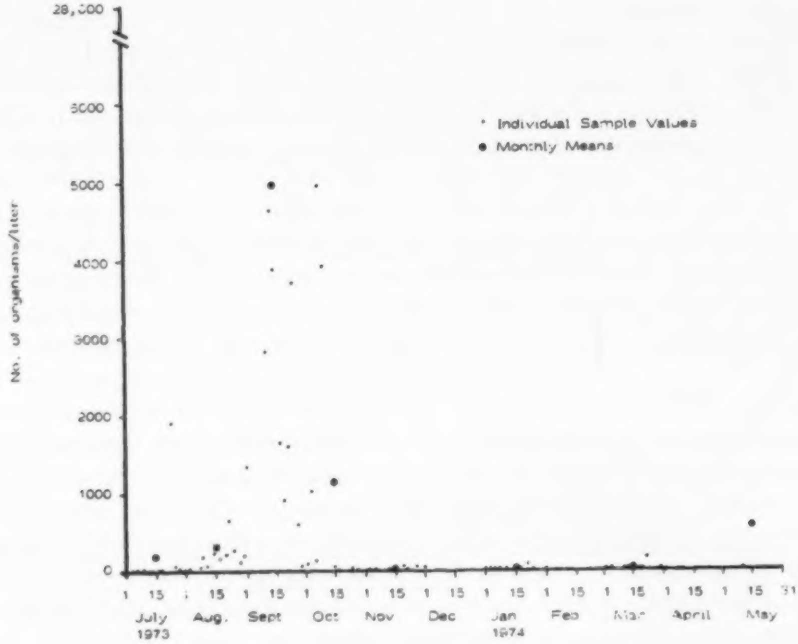


Figure 23. Myxophycean populations at Put-in-Bay.

trends since the earlier works of Chandler and Hohn. Diatoms were present in all collections; from November to May they comprised more than 90 percent of the phytoplankton population, while from July through September they made up less than 25 percent of the total population (Figure 21). Changes in the structure of the diatom population since Chandler's early work were obvious. He found that centrics, *Melosira*, *Cyclotella* and *Stephanodiscus* generally dominated fall pulses and pennates, *Asterionella*, *Fragilaria*, *Synedra*, *Tabellaria* and *Diatoma* dominated spring populations. Chandler also found *Asterionella* to be very abundant and hypothesized that the dominance of this genera in the spring could be due to a competitive advantage gained by maintaining relatively high winter populations.

During the present study the fall pulse was essentially absent and the total diatom population was strongly dominated by *Melosira* in all months but August when *Fragilaria* was slightly more abundant. *Asterionella* peaked in March 1974 at over 8,000/liter, but accounted for only 8 percent of the total phytoplankton population. It reached its greatest abundance in relation to the total phytoplankton population in November when it constituted 26 percent of the population. However, at the same time *Melosira* made up 58 percent of the population. Hohn (1969) observed that over the years *Asterionella* had not decreased in numbers, but rather other taxa, especially *Melosira*, had increased greatly causing *Asterionella* to occupy a smaller portion of the population. The present results tend to support this hypothesis; *Asterionella* population reached its highest levels in November 1973 and March to May 1974, which would correspond to the pulses observed by Chandler. Other taxa found to be abundant by Chandler, *Fragilaria*, *Synedra* and *Tabellaria*, were not found in significant numbers in this study except in December 1973 when *Fragilaria* composed 14 percent of the phytoplankton population and May 1974 when *Tabellaria* composed 23 percent of the population.

The green algae were found to be the most diverse group by earlier investigators. The major difference between the results of the present study and those of previous years was in the composition of the population. Chandler listed the taxa in order of dominance as *Dictyosphaerium*, *Schroederia*, *Scenedesmus*, *Pediastrum*, *Oocystis* and *Coelastrum*. One of these, *Dictyosphaerium*, was not observed in this study. *Pediastrum* has increased in importance as the dominant chlorophycean July through December 1973.

Chandler found that the blue-greens were very much affected by temperature and turbidity and, therefore, comparisons between years were very difficult. He listed the most common taxa of 1942 in order of abundance as *Aphanizomenon-Oscillatoria*, *Merismopedia*, *Coelosphaerium*, *Chroococcus*, and *Microcystis*. Vila-Pinto (1964) found that

Microcystis was the dominant phytoplankter during the summers of 1961-1963 with *Aphanizomenon*-*Oscillatoria* second in abundance. In the present study *Microcystis* peaked in August 1973 and represented three percent of the total phytoplankton. This was the second highest percentage for any blue-green taxa; *Aphanizomenon*-*Oscillatoria*, the most abundant blue-green taxa, which peaked in September 1973, represented 58 percent of the total phytoplankton. Chandler often found blue-greens in all samples from a particular year, whereas, none were found in samples from December 1973, February 1974, or April 1974 (Figure 23).

Zooplankton

Early studies of lake-wide zooplankton populations are not available. Wilson (Fish, 1960) studied the eastern basin in 1929-30 and Chandler (1940) investigated the western basin during the late 1930's. During the past 10 years three extensive Lake Erie zooplankton surveys have been made in addition to the present study. Davis (1969) made two transects of the entire lake (30 stations) in July and October 1967 and a partial transect in January 1968. Watson and Carpenter (1974) sampled zooplankton at 30 different stations during 10 cruises from April to December 1970 and Patalas (1972) transversed the lake sampling at 34 stations during two cruises between June and August 1972. The present study included six cruises between May and November 1974 with samples at 51 stations in the western and central basins.

Only the 1967 and 1974 surveys included rotifers in addition to crustacean zooplankton. In spite of their relatively small size, rotifers comprised a significant percentage of the zooplankton biomass (6-40 percent in the western basin). High numbers of rotifers are considered indicative of enriched conditions.

Cladocerans comprised the highest percentage of the zooplankton biomass during the late summer and fall of 1974. High populations were observed in both basins, particularly during the early summer and autumn pulses. Cladoceran numbers have increased steadily since 1939, and this group currently has higher concentrations in the western basin of Lake Erie than elsewhere in the Great Lakes. Cyclopoid copepods were dominant over calanoid copepods throughout the year. The greatest numbers of copepods occurred during June and July in both basins; this population declined steadily through November. Through the years cladocerans and cyclopoid copepods have gradually outnumbered the once dominant calanoid copepods. The trend from a calanoid-dominated to a cyclopoid- and cladoceran-dominated community has been observed in other lakes which have undergone nutrient enrichment.

Benthic Macroinvertebrate Fauna

The open water benthic fauna of Lake Erie has undergone significant changes in the past 50 years. Prior to and during the 1930's the bottom fauna of the western basin was dominated by the burrowing mayflies *Hexagenia spp.* and the caddis fly, *Oecetis inconspicua.* Other taxanomic groups were relatively unimportant by comparison, although tubificid oligochaetes were abundant near river mouths. Wright (1955), working with 1930 data, categorized the western basin into several zones of pollution based on the number of tubificid oligochaetes present: light pollution 100-999/m^2; moderate pollution 1000-5000/m^2; and heavy pollution greater than 5000/m^2. Wright classified most of the western basin as unpolluted (less than 100/m^2) whereas the mouths of the Detroit, Maumee, and Raisin Rivers were considered moderately to heavily polluted.

Revisiting Wright's stations, Carr and Hiltunen (1965) found that by 1961:

1) *Hexagenia* spp. had decreased to less than one percent of its previous abundance,

2) oligochaetes had increased ninefold in density, thereby greatly expanding the areas defined as polluted using Wright's index,

3) chironomid densities had increased fourfold, snails increased sixfold, and sphaeriid clams increased twofold.

Britt (1955) reported a drastic decline in the mayfly population during the summer of 1953 due to thermal stratification and bottom water oxygen depletion in the western basin. By 1965, Britt et al. (1973) considered *Hexagenia* spp. to be nearly extinct in the western basin. During the present study (1973-1975), no *Hexagenia* spp. were collected.

In 1963 and 1974, the U.S. Public Health Service conducted spring, summer, and fall surveys of Lake Erie (Federal Water Pollution Administration, 1968a). The FWPCA concluded that most of the western and central basins were characterized by a lack of pollution sensitive amphipods and contained a preponderance of pollution tolerant species of sludgeworms, bloodworms, fingernail clams and nematodes. The report listed 34 species in Lake Erie with an average benthos density of 1164/m^2 and 1861/m^2 for the western and central basins, respectively.

The present benthic fauna of the western basin is dominated by tubificid oligochaetes, with the genus Limnodrilus making up over 61 percent of the population. Chironomid larvae comprise the next most abundant group, nearly 20 percent of the bottom fauna. Sphaeriid clams make up less than 10 percent of the organisms, except near the Detroit River where their numbers reach 20 percent of the total population. The central basin fauna is likewise dominated by oligochaetes. Peloscolex ferox is the dominant species, but Limnodrilus spp. frequently comprise a significant portion of the populations. Chironomids form major components of the fauna, especially adjacent to the north shore (up to 30 percent). Sphaeriid clams are also abundant throughout the central basin where at times they are co-dominant with oligochaetes (up to 50 percent). Approximately 8 percent, numerically, of the benthic fauna is composed of 15 minor taxa. These include leeches, amphipods, isopods, polychaete worms, mysids, coelenterates, flatworms and caddisflies. The most common of these is the aquatic isopod, Asellus racovitzai racovitzai.

If Wright's (1955) pollution index is applied to the 1973-1975 sampling period, most of the western and central basins would be considered moderately polluted. Although the average density of the bottom fauna has nearly doubled in the decade since the USPHS 1963 and 1964 surveys (largely due to increases in oligochaetes), caution must be exercised in the application of this index to open water area of the lake where hypolimnetic anoxia can influence the benthic populations.

CONCLUSIONS

The fundamental conclusion of this assessment is that during the first half of this decade no significant decrease in the loading of nutrients to Lake Erie has taken place. Therefore, during this period the concentrations and quantities of nutrients within the waters of the lake have remained relatively stable. An encouraging sign of nutrient control is that although no decreases have been observed, the constant increases which have taken place in preceeding decades have been stopped. Other indicators of eutrophication, such as hypolimnetic oxygen depletion rates, chlorophyll concentrations, methane production, plankton and benthos populations, dissolved solids and turbidity, have remained high since 1970 but also relatively stable.

Most of the nutrient loading to Lake Erie occurs in the western basin. The largest quantity is delivered by the Detroit River, but the highest concentrations were observed near the mouth of the Maumee River. The western and central basins are effective sinks for nutrient loading; approximately 82 percent of the phosphorus carried to the lake by the tributaries remains in bottom sediments. Up to 10 percent of the phosphorus delivered to the lake can be regenerated under anoxic conditions. However, physical regeneration due to storm resuspension of sediment can have a larger impact on internal nutrient loading, particularly during non-stratified periods.

Meteorological variations such as wind, solar radiation and precipitation appear to have a much more profound effect on the trophic status of Lake Erie than attempts at nutrient control. For example in 1975, light winds during the period of thermocline formation resulted in a thicker hypolimnion in the central basin. This increased reservoir of oxygen reduced the area of anoxia by over 95 percent and thereby decreased the amount of regenerated phosphorus from the sediments by over 70 percent from the previous two years. Also, because of high concentrations of nutrients in the lake, particularly the western basin, the limiting factor in algal production appears to be sunlight. Precipitation also plays a role in nutrient concentrations; high rainfall in the early 1970's over the upper Great Lakes basins resulted in record-high flow rates in the Detroit River in 1972 and 1973. The concentration of nutrients, although not the quantity, was lowest during this period indicating dilution by excessive precipitation.

Although the effectiveness of nutrient controls in reversing eutrophication in Lake Erie cannot be demonstrated, the halting of further degradation is an important first step. Also, many of the new treatment facilities are just now being placed in operation. Modifications in agricultural practices will reduce the loading of nutrients to the tributaries, but these changes will not be reflected in water quality improvements for several years due to the slow migration of sediment to the lake. It is important that this start at improving the conditions of Lake Erie be continued and that new methods of lake restoration be explored.

TECHNICAL APPENDIX

Because of space limitations, much of the supporting data for this report could not be printed at this time. This information, largely in the form of distributional contour maps is being compiled for a Technical Appendix which will be printed in a limited quantity. The Appendix will include data on physical measurements, nutrient chemistry, bacterial activity, plankton and water quality contouring by computer graphics.

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SECTION 2

HISTORY OF LAKE ERIE WATER QUALITY

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INTRODUCTION

Documented history of Lake Erie water quality as we now consider quality standards must begin approximately with the past fifty years. Few if any technical studies of this nature exist prior to 1920. However, there are numerous recorded observations from the late 17th, through the 18th, and into the early 19th centuries. From these, water quality of the lake in those early years can be inferred. Mostly these are from the island region, the middle basin, and along the south shore.

EARLY HISTORY

Island Region

As early as 1688, one Baron de Lahontan stated that "Lake Erie assuredly 'tis the finest Lake upon earth." Many of the early reports refer to water clarity or to water color. A Captain Jonathan Carver in 1762 spoke of the many acres of large pond lilies around the islands, with leaves closely spaced and myriads of snakes on the leaves. This can mean only one thing about water clarity in those areas. It was clear and transparent. Submerged and emergent aquatics which remained in some of the south shore harbors until relatively recent years have now largely disappeared. Turbidity due to increased sedimentation, or increases in plankton populations, with consequent low light penetration have taken their toll. This transparency of the water was further substantiated in 1804 when sailors from a becalmed vessel at Middle Bass Island watched four to six pound bass take their baited hooks at fifteen feet below the surface. Again in 1804, a traveler reported Lake Erie to be a very beautiful body of water which was a beautiful deep green color and with admired transparency. The author of the statement also thought, without exception, it was the sweetest he had ever drank.

These previous reports that suggest outstanding water quality pertain mainly to off-shore waters rather than to shoreline conditions. Granted, the island region which we now consider surrounded by low quality water was involved, but one must remember that these islands were largely unpopulated except for Indians who hunted there winters.

Inshore Regions

The quality of inshore waters can be readily inferred when one visualizes the Cleveland, Ohio area with its 16 dwellings in 1811 as reported by John Melish. The river (Cuyahoga) was stagnant, contaminated with decaying vegetables (algae?, aquatics ?) and putrid animal substances. The odor was almost insufferable. The discharge of this effluent into the lake certainly must have occurred. It probably was no better when Maximilian, on 23 June 1834 reported "the dark brown waters of the Cuyahoga are strongly contrasted to a considerable distance with those of the lake." This condition of inshore water is further substantiated by James Flint who wrote in October 1820 that at Venice on the south shore, confervae (algae) washed ashore by wind and waves, and that this debris emitted disagreeable effluvia. In modern terms, it stank. Though the alga *Cladophora* was not identified as such by Bailey until 1848, there is no reasonable doubt that Flint's "confervae" (a term used at that time for any algae) was *Cladophora*. It also points up the fact that *Cladophora* was extant along the beaches in quantities similar to what we experience today along all stable shores. John Havison in 1822 had previously reported Lake Erie beaches strewed with dead fish and shells. Water quality along beaches could not have been of the best.

Our knowledge of inshore water quality in 1828 is further extended by J.J. Bigsby who wrote that Lake Erie inshore water in a gale is rendered turbid by sand and mud from the bottom, but that water some distance into the lake is good. Also, in summer, near shore it (water) is much contaminated with animal and vegetable matter in a state of putrification. Turbidness after storms appears to have been one of the most noticeable characters of Lake Erie water. Daniel Drake again referred to it in 1842 when he wrote that shallow Lake Erie was less transparent than the deeper lakes above, and that wind agitates it to the bottom with slime being thrown up. Though inshore water was undesirable for domestic use, water that entered the lake from the Maumee River in 1873 must have been potable as Toledo used raw water from the river in city mains.

Swamp Regions

The first reference to water temperature is by Bigsby in 1828 when he stated that shoal water is heated to temperatures from 90° to 95° and that the steaming swamps of western Lake Erie are universally full of putrifying substances. These occasion "prevalent bilious remittments." Today most of the swamps are gone and water temperatures probably seldom exceed 80° F.

An early reference to the "Black Swamp" whose history is intimately interwoven with that of western basin water quality was by Daniel Drake in 1848. He described the immensity of the area, the huge forest trees, the rotting vegetation, and the stagnant, black water. Martin Katz gives us further insight into the swamp and what its destruction by clearing and draining from late 1850 on into 1870 meant to the lake.

This black, highly nutrient loaded water flowed through Maumee Bay into the western basin where it increased turbidity, sedimentation, color, and the nutrient load. The accelerated deterioration of water quality in Lake Erie's western basin may well have begun with this event.

Pollutants

The first recorded indication of deteriorating water quality caused by increasing phytoplankton was what was probably an algal bloom in 1859. August A. Fahnestock commented on the "green scum" of Maumee Bay. It was also about that period that Toledo was known as "frogtown" because of immense numbers of frogs that swarmed over the town from the vegetation choked shorelines.

Another report that specifically refers to water quality in the western basin was by Thomas Blackwell in 1866. He wrote that a moderate gale raises a sea in Lake St. Clair which becomes turbid from detrital matter from the muddy bottom. This is then distributed through the Detroit Straits into Lake Erie where ordinary storms also disturb the bottom and redistribute sediments (and their nutrient load).

A much greater water quality problem arose sometime around 1900 when C.E. Slocum reported in 1903 significant contamination of water by mineral salts and petroleum from wells along tributary streams. Previous to that date, in 1894, fishermen were complaining that petroleum from adjacent oil fields was responsible for a decline in fishing. The problem became worse rather than better if we are to believe G.M. Grant's rather dramatic statement in 1922. He stated, "Odors and sediments of oils, sewage, and wastes so fouled the water and bottom in the west end of Lake Erie, fish can no longer find food or live in poisoned areas. Thousands of dead fish are on the surface. The same conditions contain along Lake Erie's entire coastal front." According to D.L. Anthony who wrote in

1922, the fishing industry reached its zenith about 1854. However the noticeable disappearance of herring did not begin until 1889-90 while whitefish and catfish declined after 1880. Whether these declines were associated with the purported decline in water quality at about that time is debatable.

WATER QUALITY AND SEDIMENT STUDIES

Degradation of water quality before 1900 is further evidenced when Herbert S. Jenning, in his study of the algae of western Lake Erie, remarked that the surface of the west end was covered by a green layer. He certainly referred to a "bloom", and one which was much more extensive than that reported off Toledo in 1859. Tiffany discussed the occurrence of blooms during the 1920's while the author saw a bloom of blue-green algae that extended over the entire west end of the lake in 1933. Recent years have seen periodic occurrences of blooms; some more, some less intense and extensive. The latest of great extent occurred during the summer of 1970.

The pre- or early 1900 studies that involved water quality in Lake Erie were either localized, for short periods, or limited mostly to observations that concerned taxonomy. Quantitative data are scarce.

History of water quality in Lake Erie during the past three quarters of a century really begins with the study by Stillman Wright and his associates, L.H. Tiffany, and Wilbur M. Tidd between 1926 and 1930. No comprehensive survey of the physical, chemical, and biological conditions had been made prior to that study.

The first sediment study was made by Moseley in 1904. His work, in conjunction with observations made in 1850, and with our present knowledge, lead to an estimated 3 fold increase in sedimentation rate during the past century. The fact that Lake Erie, in 1922, had a two year average of 2,200 mg/m^3 dry organic matter as contrasted to an oligotrophic lake in Wisconsin having an average of 880 mg/m^3 for the same period accentuates the increase. This increase had had a pronounced effect on oxygen demand in the Lake. Wright found oxygen depletion during three seasons to be generally of minor importance. Today its depletion in the western and central basins where zero levels have been observed frequently since 1961 is a major concern. One of the most quantitative measures of water quality degradation in Lake Erie since the turn of the century has been the increase in the O_2 depletion rate in the hypo-limnion of the central basin. This is estimated to have been about 3 percent per year during the past twenty years.

The concentration of total dissolved solids, a gross indication of water quality, has increased significantly from 133 mg/l to 198/mg/l during the past half century. Historical data point to marked increases of chemicals occurring in the Lake since 1910. There are no historic data on total loading of phosphorous in earlier years, but some evidence exists that soluble reactive phosphorous levels increased by four times between 1942 and 1967. This is understandable when one considers that only 16 percent of the P entering Lake Erie leaves through the outlet. Total nitrogen, another serious water quality degrading factor, increased three fold between 1930 and 1958, while a five fold increase in open lake ammonia occurred during the same period, and a thirteen fold increase in the latter from 1942 to 1968. Chloride concentration at 6 ppm in 1900 stood at 25.6 ppm in 1963, while sulfate at 12 ppm in 1900 reached 23 ppm in 1960, of which 11 ppm of the latter had occurred in the last thirty years.

Concentrations of Si, Al, K, Na and Mg have not changed appreciably since 1850 as evidenced by studies of cores. However, Hg, Pb, Zn, Cd, Cu, and organic C, N, P have all increased due to loading in the lake since 1850. In general, loading of mercury since 1950 has been extremely critical for water quality. Current loadings of organic carbon to the eastern basin is estimated to be five times that of colonial times, with the 0_2 depletion rate increasing.

SUMMARY

The history of Lake Erie, and especially that of the western basin, has been one of eutrophication and degradation of water quality throughout its existence. It was the most productive of the Great Lakes and probably was mesotropic because of its shallow basin even before its shores were invaded by Europeans. Data indicate major increases in loading began a few years prior to 1940, with loadings continuing to increase since. The years during and immediately following World War II were particularly critical because of increased industrial production with attendant increases in waste disposal. If Cladophora is an indication of degradation (which may or may not be true), then observations by fishermen as well as others, of increases in Cladophora along shore lines during the late 1940's tend to support degraded water quality.

Some historical data however, indicate that marked increases in chemicals occurred after 1910. The chemicals, if the I.J.C. report of 1913 is accepted, were not industrial pollutants as that report stated; these types were not in sufficient quantities to affect water use. They must have been domestic and agricultural related.

The question is not, has water quality in Lake Erie changed, but rather, how much degradation has occurred since Lake Erie was first seen by European travelers? The historic fact is that Lake Erie water not only has changed, but has changed drastically. Furthermore, the change in water quality accelerated once Europeans invaded the lake and its environs.

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SECTION 3

OXYGEN DEPLETION AND ANOXIA IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE, 1973 - 1975

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INTRODUCTION

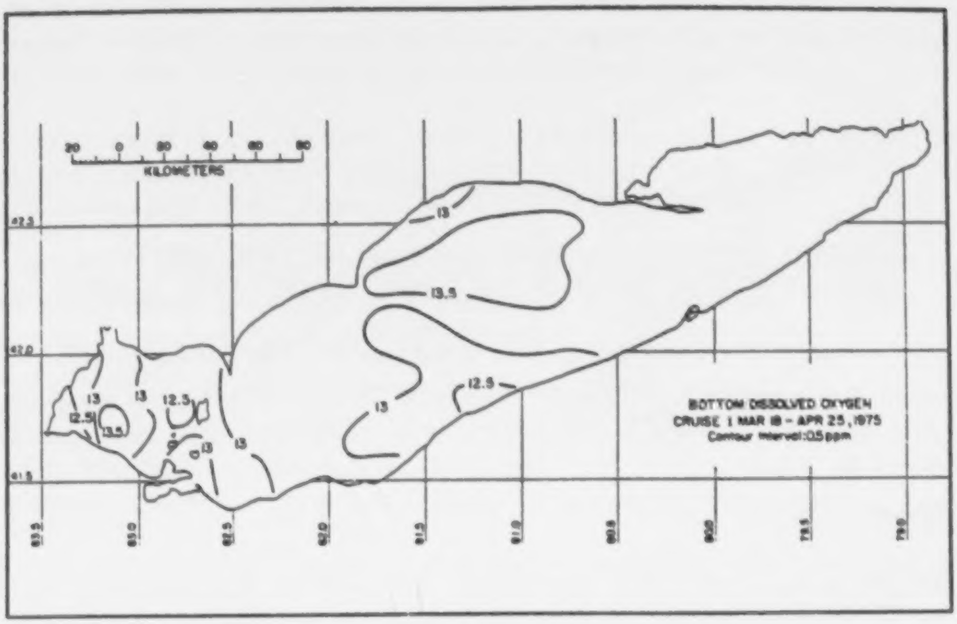
From spring until fall turnover, the central and western basins of Lake Erie show a steady decline in the concentration of dissolved oxygen (Figures 24-27). These changes are initially a change in the solubility of dissolved oxygen due to warming of the water column. The central basin, because of its middle latitude and moderate depth, stratifies into a thick epilimnion (15-17 m) relative to the hypolimnion (4-8 m). The intervening mesolimnion (thermocline) retards mixing of dissolved substances between the adjacent layers. In 1974 and 1975 the hypolimnetic concentration of dissolved oxygen in the central basin diminished from a basin average of 80-85 percent saturation in early June to 12-29 percent by early September (Tables 14-16). A hypolimnetic saturation of three percent was estimated for early September 1973 (Table 14). Thereafter, with the onset of fall turnover, bottom oxygen values increased (Figures 28-29).

DEPLETION RATES

Central Basin Oxygen Depletion

The steady depletion of dissolved oxygen within the hypolimnion of the central basin was due to bacterial oxidation or organic material (88 percent of depletion rate in 1970) and the oxidation of reduced metallic species (12 percent of depletion rate in 1970, Burns and Ross 1972). However, the magnitude of the depletion rate in this basin can be masked by any of several events, these include:

1) Volumetric changes of the hypolimnion caused by the loss or gain of water, including dissolved oxygen to or from the overlying mesolimnion.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KILOMETERS
42.5
42.0
41.5
13
13.5
12.5
13
13
12.5
13
12.5
13.5
13
13
13
BOTTOM DISSOLVED OXYGEN
CRUISE 1 MAR 18 - APR 25, 1975
Contour interval: 0.5 ppm
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0

Figure 24. Bottom dissolved oxygen, cruise 1, March 18-April 25, 1975.

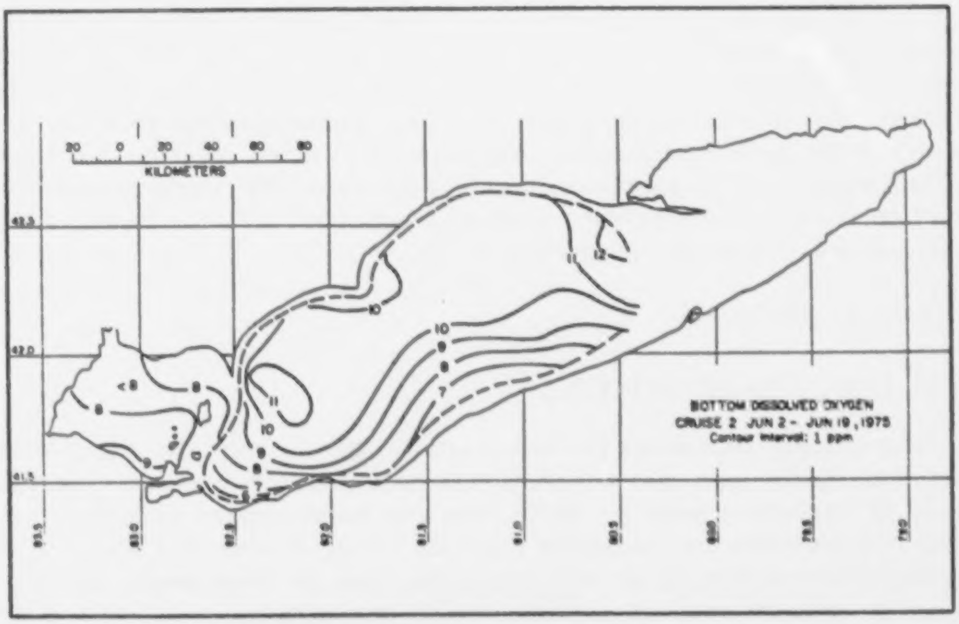
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
11
12
10
10
9
8
7
11
10
9
8
7
6
<8
8
8
9
BOTTOM DISSOLVED OXYGEN
CRUISE 2 JUN 2 - JUN 19, 1975
Contour interval: 1 ppm
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0

Figure 25. Bottom dissolved oxygen, cruise 2, June 2-June 19, 1975.

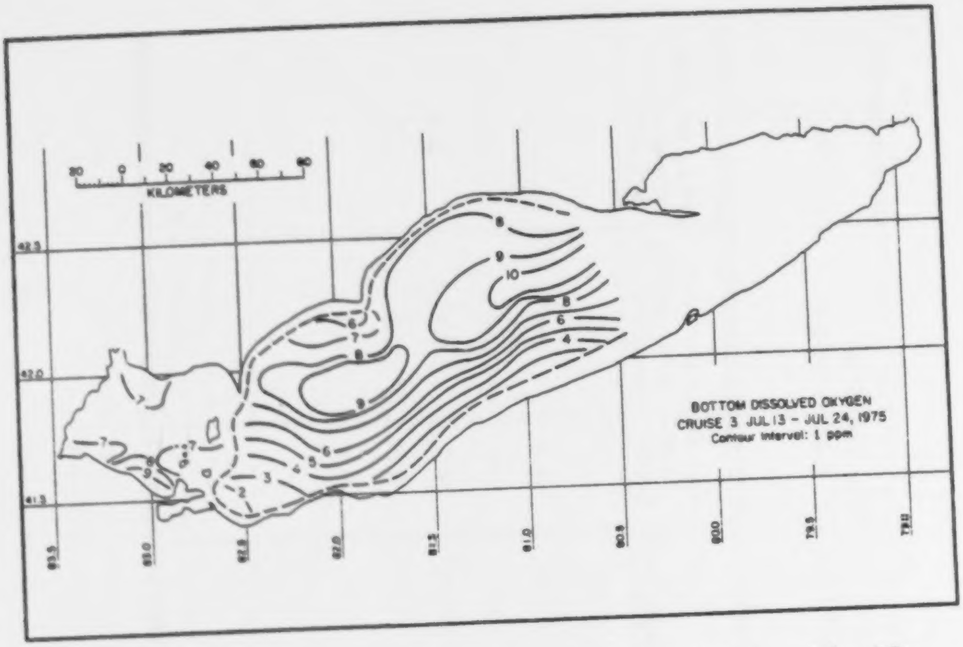
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
8
9
10
8
6
4
6
7
8
9
7
7
8
9
6
5
4
3
2
BOTTOM DISSOLVED OXYGEN
CRUISE 3 JUL 13 - JUL 24, 1975
Contour Interval: 1 ppm

Figure 26. Bottom dissolved oxygen, cruise 3, July 13-July 24, 1975.

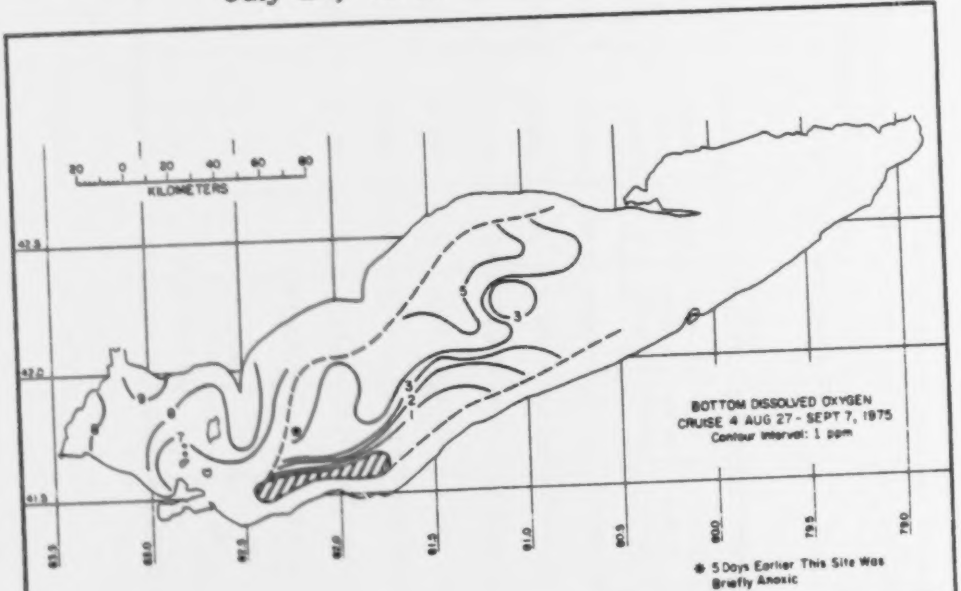
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
5
3
3
2
1
8
8
8
7
9
BOTTOM DISSOLVED OXYGEN
CRUISE 4 AUG 27 - SEPT 7, 1975
Contour Interval: 1 ppm
* 5 Days Earlier This Site Was Briefly Anoxic

Figure 27. Bottom dissolved oxygen, cruise 4, August 27-September 7, 1975.

TABLE 14. SUMMARY OF 1973 HYPOLIMNETIC SURVEYS OF THE CENTRAL BASIN OF LAKE ERIE

Cruise	Dates	Area (km^2)	Volume (km^3)	Ave. Thick. (m)	Total Heat ($kcal \times 10^{12}$)	Ave. Temp. (^oC)	Total O_2 ($kgO_2 \times 10^6$)	Ave. O_2 Conc. (ppm)	Ave. Temp. Grad. Across Meso. ($^oCm^{-1}$)	Ave. O2 Meso. Across Meso. (gO_2m^{-4})
1	6/30–7/2	Incomplete Data								
2	7/17–7/21	12,883	61.6	4.8	636.1	10.3	300.3	4.9	5.2	1.7
3	7/25–7/28	Incomplete Data								
4	8/7–8/11	12,962	60.8	4.7	721.6	11.9	167.0	2.7	6.7	2.4
5	8/29–9/4	11,829	47.1	4.0	556.8	11.8	14.9	0.3	5.6	3.0
6	9/23–9/29	3,660	11.3	3.1	151.3	13.3	12.3	1.1	2.9	4.0
7	10/14–10/24	Unstratified								
8	11/7–11/15	Unstratified								
9	12/4	Unstratified								

TABLE 15. SUMMARY OF 1974 HYPOLIMNETIC SURVEYS OF THE CENTRAL BASIN OF LAKE ERIE

Cruise	Dates	Area (km^2)	Volume (km^3)	Ave. Thick. (m)	Total Heat ($kcal \times 10^{12}$)	Ave. Temp. (°C)	Total O_2 ($kgO_2 \times 10^6$)	Ave. O_2 Conc. (ppm)	Ave. Temp. Grad. Across Meso. ($^{\circ}Cm^{-1}$)	Ave. O2 Meso. Across Meso. (gO_2m^{-4})
1	4/7–4/17		Unstratified							
2	4/25–5/4		Unstratified							
3	5/14–5/24		Unstratified							
4	6/1–6/10	14,819	91.9	6.2	794.7	8.7	910.8	9.9	1.9	1.4
5	6/30–7/7	11,860	49.1	4.1	524.4	10.7	352.1	7.2	6.0	2.4
6	7/26–8/6	12,538	62.8	5.0	800.6	12.8	196.6	3.1	5.6	3.4
7	8/12–8/19	11,698	50.6	4.3	687.2	13.6	104.6	2.1	5.5	3.6
8 *	8/26–9/7	10,556	48.8	4.6	673.2	13.8	34.6	0.7	7.4	6.0
9	9/24–9/27		Unstratified							
10	10/21– 11/1		Unstratified							
11			Unstratified							

* Turnover occurred during Cruise 8.

TABLE 16. SUMMARY OF 1975 HYPOLIMNETIC SURVEYS OF THE CENTRAL BASIN OF LAKE ERIE

Cruise	Dates	Area (km^2)	Volume (km^3)	Ave. Thick. (m)	Total Heat ($kcal \times 10^{12}$)	Ave. Temp. (°C)	Total O_2 ($kgO_2 \times 10^6$)	Ave. O_2 Conc. (ppm)	Ave. Temp. Grad. Across Meso. ($°Cm^{-1}$)	Ave. O2 Meso. Across Meso. (gO_2m^{-4})
1	3/27–4/25		Unstratified							
2	6/9–6/16	13,680	104.7	7.7	684.0	6.5	1047.7	10.0	4.0	0.2
3	7/13–7/20	13,385	90.5	6.8	708.7	7.8	697.7	7.7	6.0	0.7
4	8/27–9/5	9,600	66.1	6.9	673.7	10.2	216.5	3.3	6.5	3.4
5	9/29–10/6		Unstratified							
6	12/2 – 12/14		Unstratified							

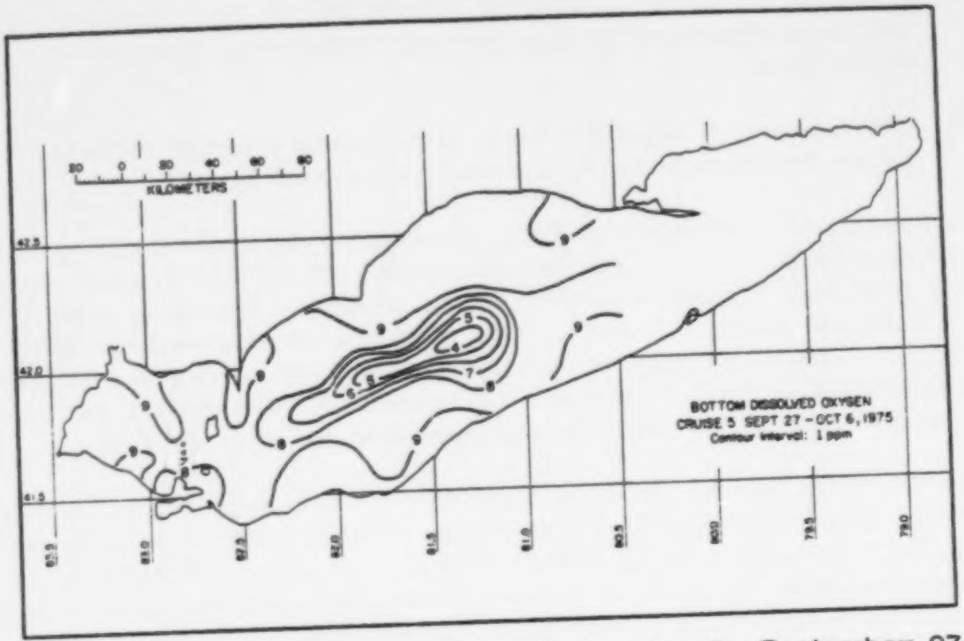
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
9
9
9
9
9
8
8
8
5
4
7
6
6
BOTTOM DISSOLVED OXYGEN
CRUISE 5 SEPT 27 - OCT 6, 1975
Contour interval: 1 ppm
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0

Figure 28. Bottom dissolved oxygen, cruise 5, September 27-October 6, 1975.

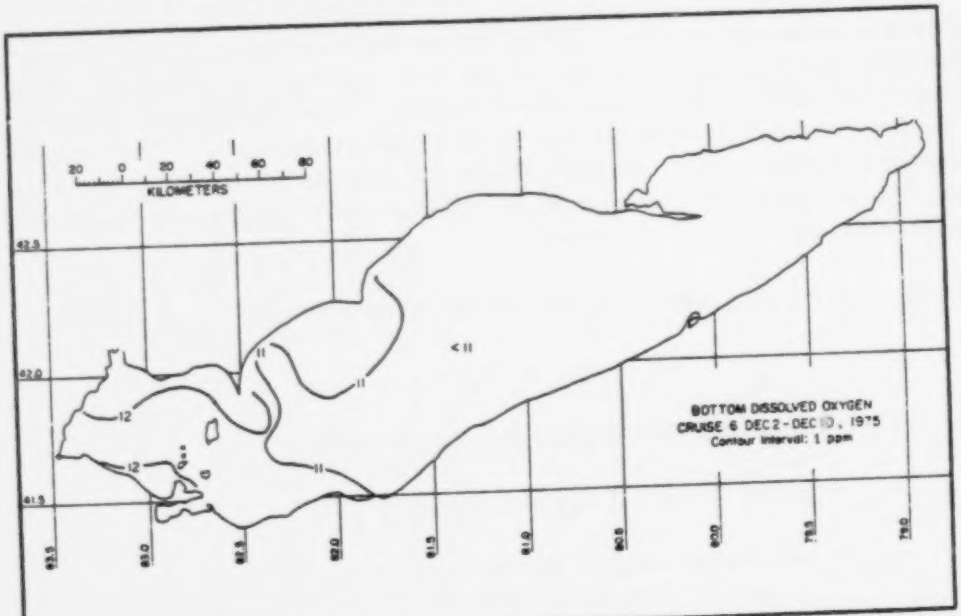
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
11
<11
11
12
12
11
BOTTOM DISSOLVED OXYGEN
CRUISE 6 DEC 2 - DEC 10, 1975
Contour interval: 1 ppm
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0

Figure 29. Bottom dissolved oxygen, cruise 6, December 2-December 10, 1975.

2) Exchange of water between the mesolimnion and hypolimnion, including dissolved oxygen, without volumetric changes in either layer.

3) Entrainment of adjacent basin and tributary water masses within the hypolimnion, including dissolved oxygen.

Temperature profiles (Figures 7-8) show a seasonal lowering of the thermocline at hypolimnetic volume loss. Estimated hypolimnetic volumes (Figure 9) generally follow this trend but fluctuate within a year or between years. Additionally, evidence of downwellings (Figures 10-11), upwelling (Figure 12) and entrainment of oxygenated waters in the southeast portion of the basin (Figures 13-14) indicate the central basin hypolimnion as an occasionally open and dynamic system.

Burns (1976) has proposed a Mesolimnion Exchange Model to more accurately determine the oxygen depletion rate by estimating and correcting for exchanges with the hypolimnion. A sample calculation is presented in Table 4. Due to a lack of accurate estimates, calculations presented here neglect entrainment of eastern basin waters. Thus, 1973 and 1974 values presented in Table 5 are somewhat conservative (1975 oxygen contours show no evidence of this phenomenon).

Average volumetric rates of 0.12, 0.13, and 0.10 g $O_2 m^{-3} day^{-1}$ and average areal rates of 0.53, 0.60 and 0.67 g $O_2 m^{-2} day^{-1}$ were calculated for 1973, 1974, and 1975 respectively (estimates of 1973 rates are not based on the entrie stratification period). The apparent improvement experienced in 1975 must be viewed critically, as a simple student T-test shows no difference in 1973 - 1975 depletion rates that are detectable by statistical means.

Burns (1976) suggests the following relationship:

$$O_v = K_w + K_s/d$$

where, O_v = volumetric oxygen delpletion rate

K_w = water column oxygen demand

K_s = sediment oxygen demand

d = mean hypolimnetic depth

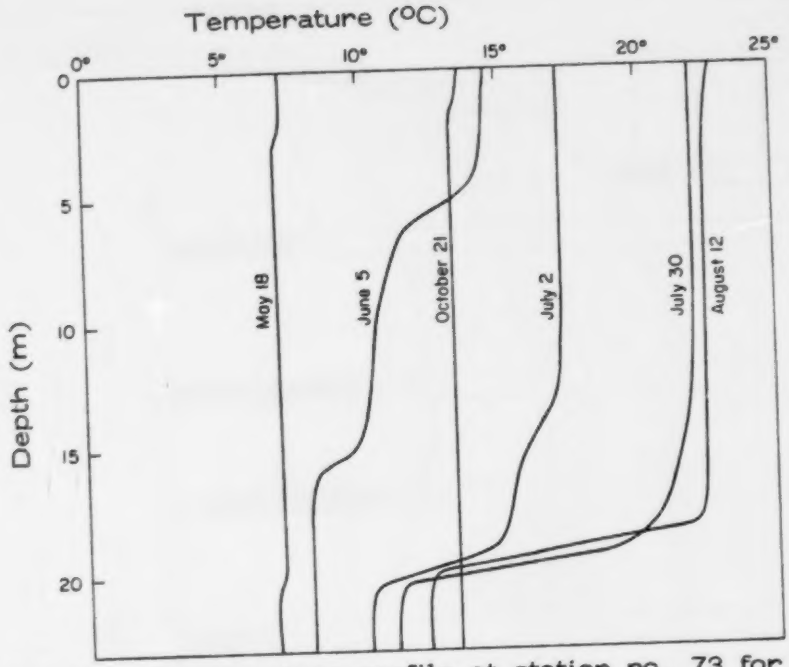

Figure 30. Temperature profile at station no. 73 for May-October 1974.

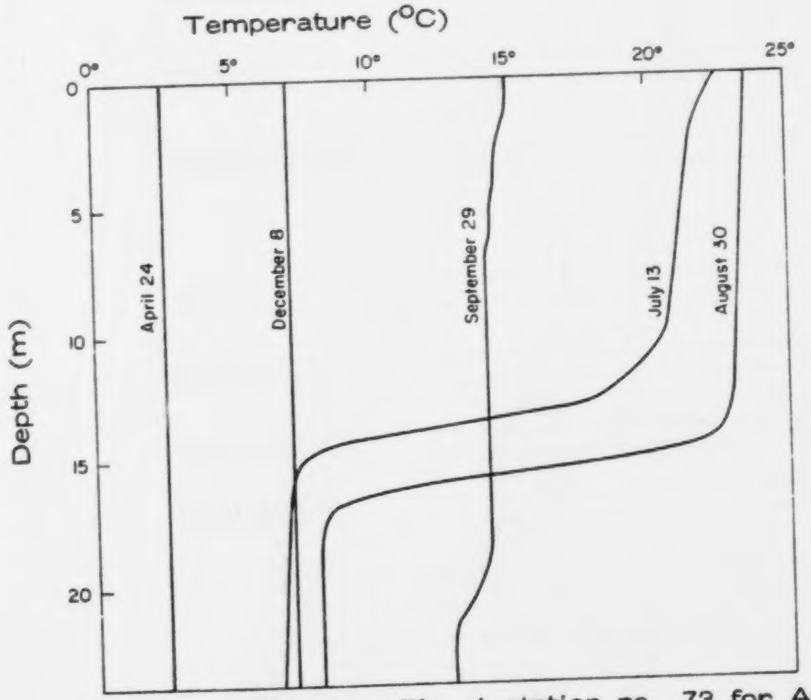

Figure 31. Temperature profile at station no. 73 for April-December 1975.

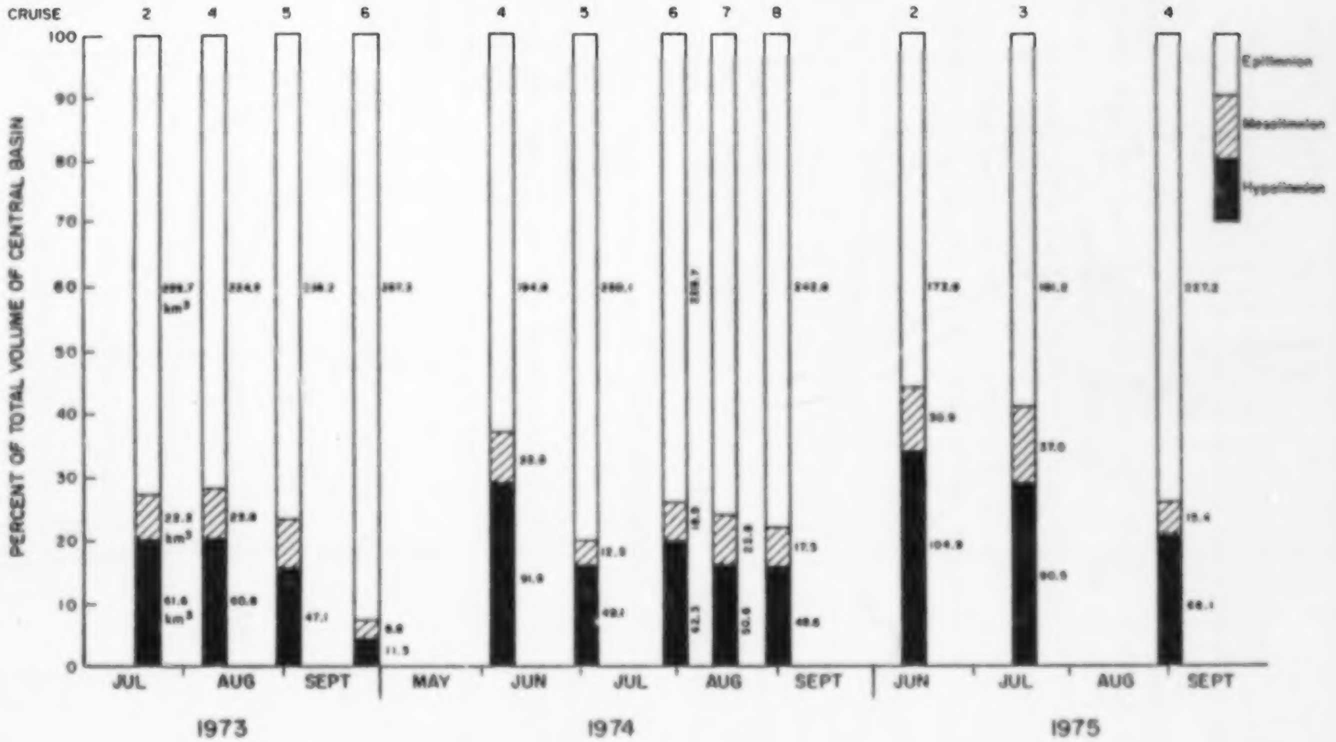

Figure 32. Volume comparison for stratification layers in the central basin of Lake Erie 1973-1975.

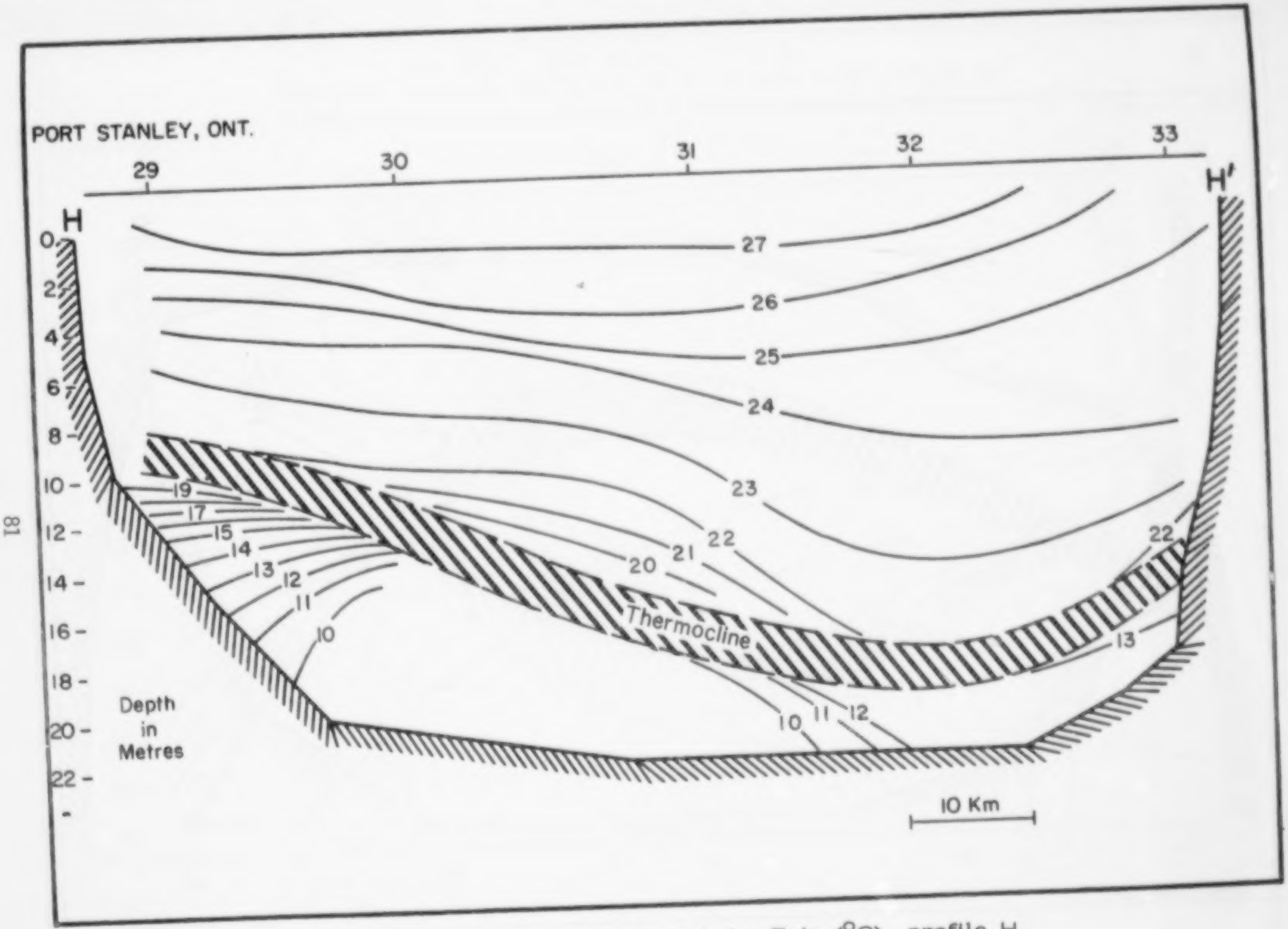

Figure 33. Thermal structure of Lake Erie (^{o}C), profile H, cruise 5, September 3, 1973.

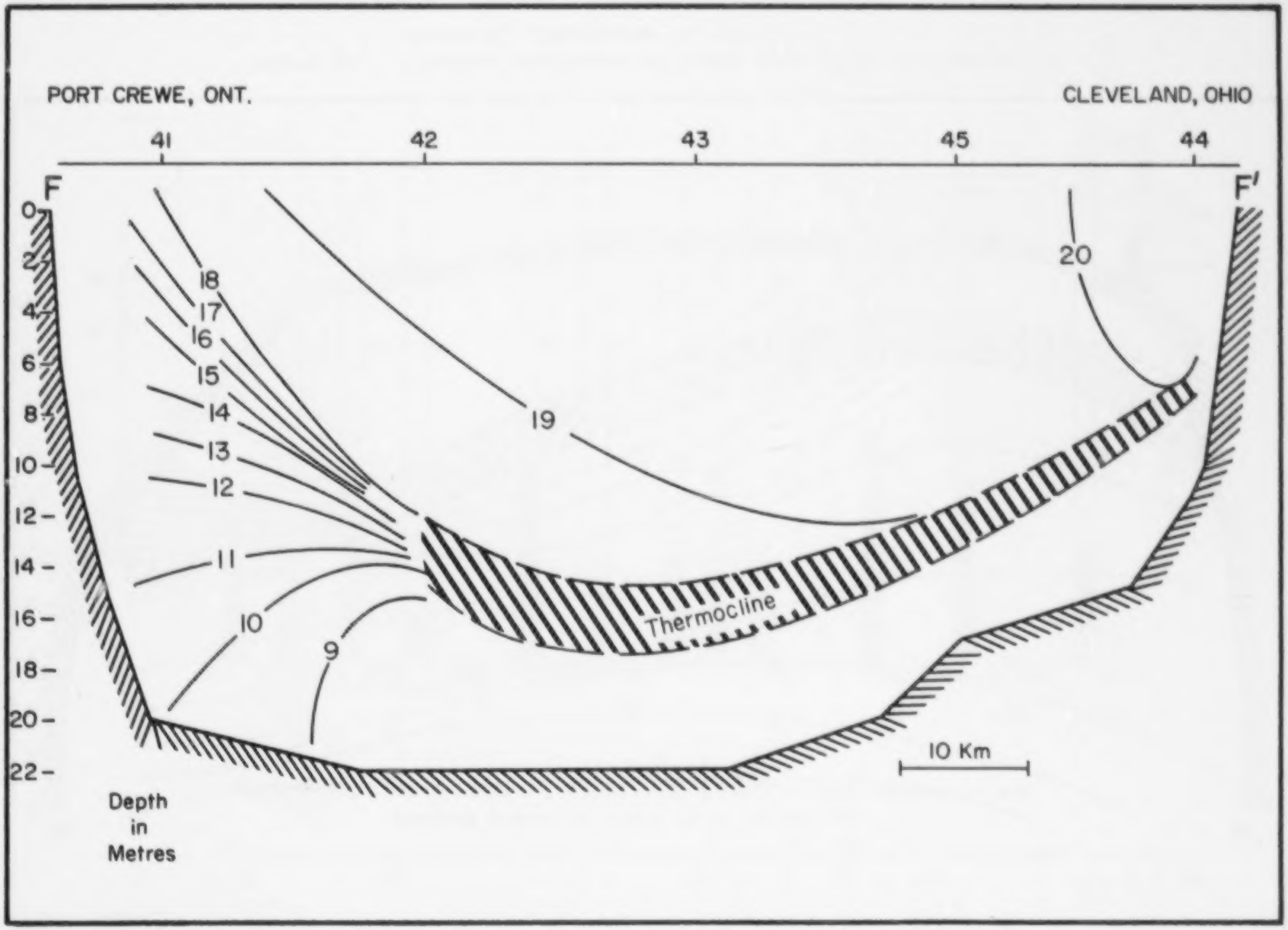

Figure 34. Thermal structure of Lake Erie (°C), profile F, cruise 1, June 30–July 1, 1973.

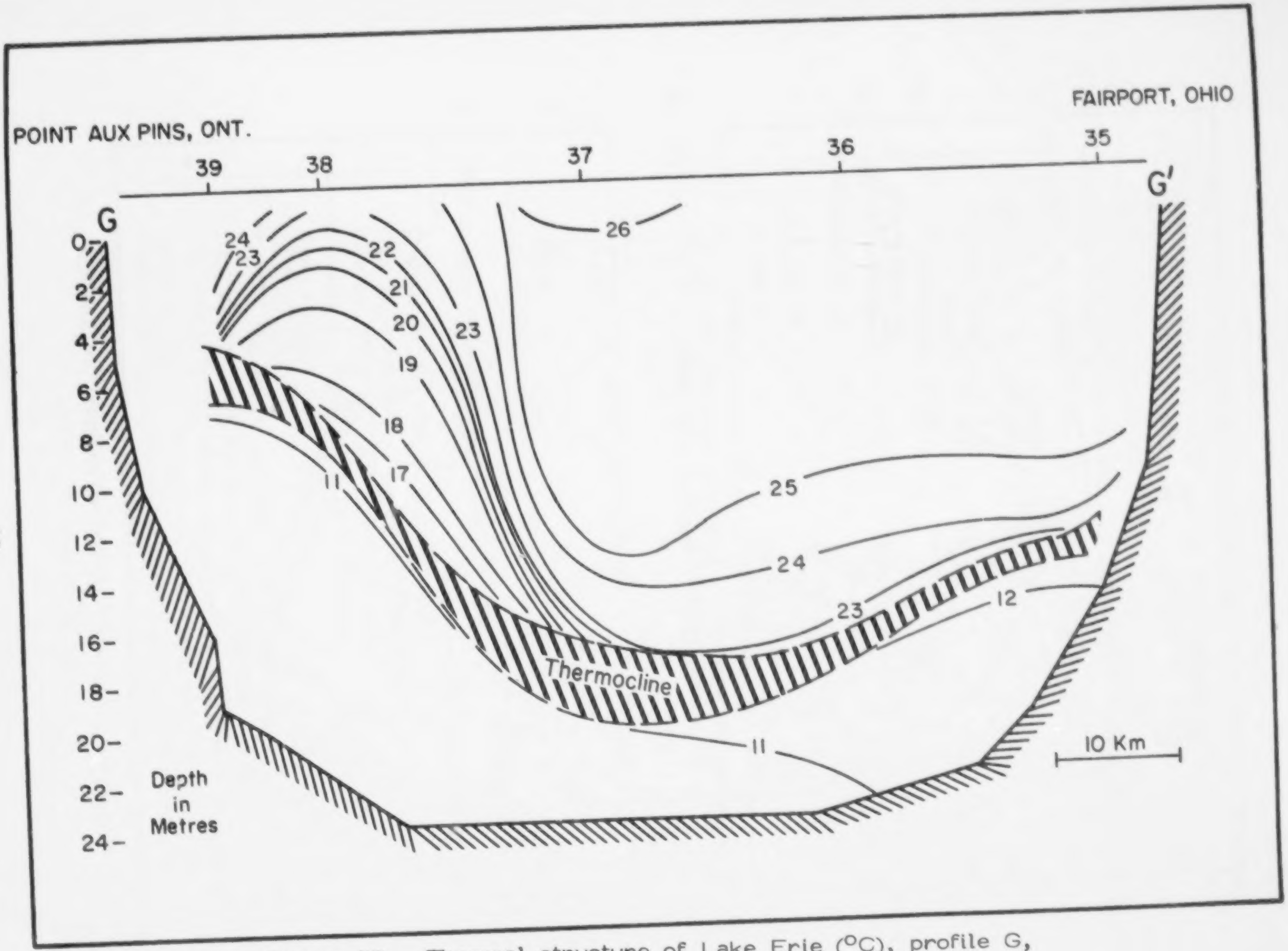

Figure 35. Thermal structure of Lake Erie (°C), profile G, cruise 4, August 9, 1973.

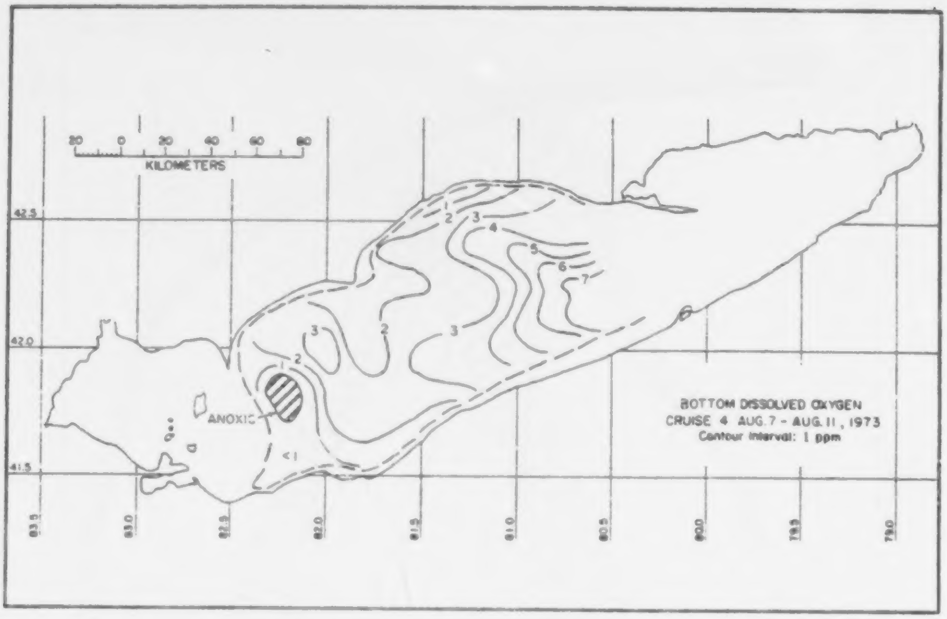
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
2
3
4
5
6
7
ANOXIC
<1
BOTTOM DISSOLVED OXYGEN
CRUISE 4 AUG. 7 - AUG. 11, 1973
Contour interval: 1 ppm

Figure 36. Bottom dissolved oxygen, cruise 4, August 7-August 11, 1973.

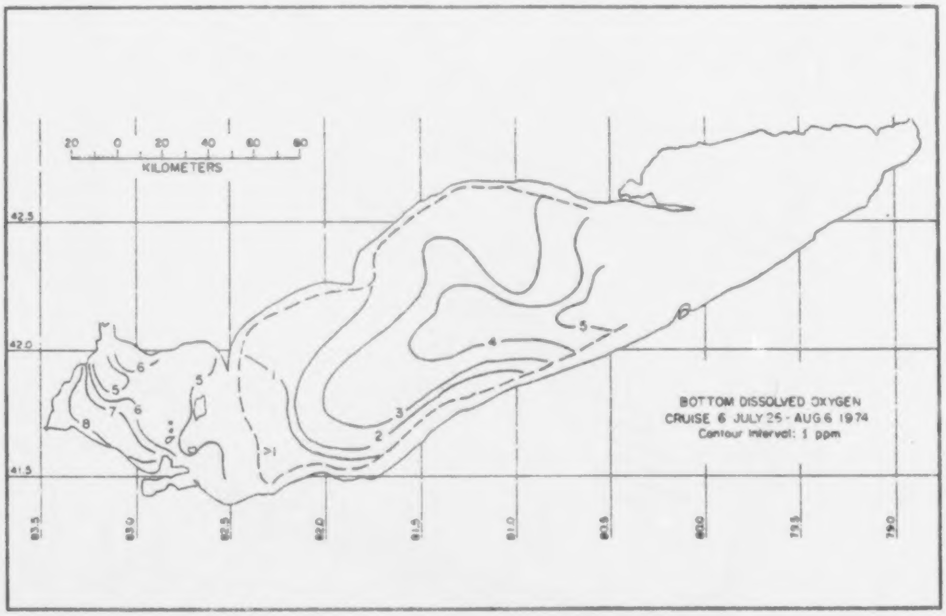
20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
2
3
4
5
6
7
8
>1
BOTTOM DISSOLVED OXYGEN
CRUISE 6 JULY 25 - AUG 6 1974
Contour interval: 1 ppm

Figure 37. Bottom dissolved oxygen, cruise 6, July 26-August 6, 1974.

TABLE 17. SAMPLE CALCULATION FOR MESOLIMNION EXCHANGE MODEL FOR LAKE ERIE HYPOLIMNION OXYGEN DEPLETION FOR JULY 16-SEPTEMBER 1, 1975

1. Hypolimnetic area (km^2) and volume (km^3):

	Area	Volume
Cruise 3 =	13,385	90.49
Cruise 4 =	9,599	66.07
Mean	11,492	78.28
Decrease	3786.0	24.42

2. Mean temperature (°C) and dissolved oxygen ($g\ O_2\ m^{-3}$) of upper hypolimnion:

	Temperature	Oxygen
Cruise 3 =	7.98	7.39
Cruise 4 =	11.21	3.55
Mean	4.60°C	5.47 $g\ O_2\ m^{-3}$

3. Hypolimnetic losses during volume decrease:

Heat

$$9.60^{\circ}C \times 24.42\ km^3 = 234.43 \times 10^{12}\ kcal.$$

Oxygen

$$5.47\ g\ O_2\ m^{-3} \times 24.42\ km^3 = 133.58 \times 10^6\ kg\ O_2$$

4. Heat budget of hypolimnion ($\times 10^{12}$ kcal):

Cruise 3 =	708.67	(observed)
Cruise 3-4=	-234.43	(calculated loss)
Cruise 4 =	474.24	(anticipated)
Cruise 4 =	673.66	(observed)
discrepancy	199.42	

Note: the above considers that heat loss to sediments and heat conducted into the hypolimnion by thermal conduction to be insignificant when compared to the above values and roughly equal, therefore cancelling each other. (Burns and Ross, 1972). The discrepancy (anticipated-observed) is assumed to be the result of water exchanged with the mesolimnion (= exchange heat).

(continued)

TABLE 17 (continued)

5. Mean temperature ($^{\circ}C\ m^{-1}$) and dissolved oxygen ($g\ O_2\ m^{-4}$) gradients of the mesolimnion:

		Temperature	Oxygen
Cruise 3	=	6.06	0.69
Cruise 4	=	6.46	3.36
Mean		6.26	2.03

6. Dissolved oxygen added to hypolimnion by exchanges with the mesolimnion:

$$\frac{2.03\ g\ \ m^{-4}}{6.26^{\circ}C\ \ m^{-1}} \times 199.42 \times 10^{6}\ m^{3}\ ^{\circ}C = 64.67 \times 10^{6}\ g\ O_2$$

7. Dissolved oxygen budget ($\times 10^{6}$ kg O_2) of hypolimnion:

Cruise 3 = 697.72 (observed)
Cruise 3-4 = -133.58 (calculated loss)
Cruise 3-4 = + 64.67 (calculated gain)
Cruise 4 = 628.81 (anticipated)
Cruise 4 = 216.52 (observed)
discrepancy 412.29

Note: discrepancy is assumed to be the result of internal oxygen depletion.

8. Areal depletion rate:

$$\frac{412.29 \times 10^{6}\ kg\ O_2}{11,492\ km^{2}} \times \frac{1}{45^{*}\ days} = 0.80\ \ g\ O_2\ m^{-2}\ day^{-1}$$

* Days between the midpoint dates of Cruise 3 and 4.

9. Volumetric depletion rate:

$$\frac{412.29 \times 10^{6}\ kg\ O_2}{78.28} \times \frac{1}{45\ days} = 0.12\ \ g\ O_2\ m^{-3}\ day^{-1}$$

TABLE 18. HYPOLIMNETIC OXYGEN DEPLETION RATES IN THE CENTRAL BASIN OF LAKE ERIE (1973-1975)

Cruise	Intercruise Period (Days)	Mesolimnion Exchange Model Area	Mesolimnion Exchange Model Volumetric	Net Volumetric Depletion Rate
1973				
2–4	21	−0.60	−0.13	−0.10
4–5	23	−0.46	−0.10	−0.10
Mean		−0.53 ± 0.10	−0.12 ± 0.02	−0.10 ± 0.01
1974				
4–5	26.5	−0.66	−0.13	−0.10
5–6	27.5	−0.85	−0.19	−0.15
6–7	15	−0.46	−0.10	−0.07
7–8	16.5	−0.42	−0.09	−0.07
Mean		−0.60 ± 0.20	−0.13 ± 0.05	−0.10 ± 0.04
1975				
2–3	34	−0.53	−0.07	−0.07
3–4	45	−0.80	−0.12	−0.10
Mean		−0.67 ± 0.19	−0.10 ± 0.04	−0.09 ± 0.02

Areal Rates: g O_2 $m^{-2}day^{-1}$.

Volumetric Rates: g O_2 $m^{-3}day^{-1}$.

Based on the small probability that an apparent improvement did occur, several explanations are possible using this relationship. Although Blanton and Winklhofer (1972) failed to note dissolved oxygen fluctuations in the water column due solely to the presence of algae, Lucas and Thomas (1972) noted diurnal fluctuations in the sediment oxygen demand in the central basin. Oxygen, produced by algae offset the sediment oxygen demand rate by as much as 0.6 - 0.7 gm $O_2 \cdot day^{-1}$. A mean corrected chlorophyll a value for the hypolimnion in 1975 was 92 percent greater than recorded in 1974 (Fay, 1976).

The sediment-water interface of the central basin has been cited as the major site of bacterial activity (Menon et al. 1972). The overall volumetric depletion rate includes oxygen depleted at this interface plus the oxygen consumed or produced in the hypolimnetic water column. Therefore, as the thickness of the hypolimnion becomes small, the normally larger sediment oxygen demand plays a larger role in determining the overall rate. The average thickness of the hypolimnion during stratification was 7.1 m in 1975 and only 4.9 in 1974. Thus, an apparent improvement in the volumetric depletion rate may only reflect the increased hypolimnetic thickness.

The volumetric depletion rate of the central basin has been suggested as an indicator of the trophic state of the lake (Dobson and Gilbertson, 1972). Depletion rate values have reached and oscillated around a value of 0.12 - 0.13 g $O_2 \cdot m^{-3} \cdot day^{-1}$, since the early 1960's (Figure 38). However, to determine a genuine improvement in the depletion rate (due to the influence and vagarity of meteorological conditions), Burns (1976) stated that this rate must be measured to an accuracy of ± 3 percent for five consecutive years (assuming an annual decrease of 0.0025 g $O_2 \cdot m^{-3} \cdot day^{-1} \cdot year^{-1}$). Thus, no improvement in the trophic state of Lake Erie, using the volumetric depletion rate has been discerned in the first half of the 1970's. Present areal deficit rates place the central basin in the eutrophic state (i.e. $>$0.55 g $O_2 \cdot m^{-2} \cdot day^{-1}$, Hutchinson 1957).

Western Basin Oxygen Depletion

Due to the transitory nature of stratification in the western basin, measures of an oxygen deficit rate were not possible. Data collected in 1973 and 1975 indicate that the sediment oxygen demand in this basin remains high and continues to become depleted of oxygen under appropriate conditions.

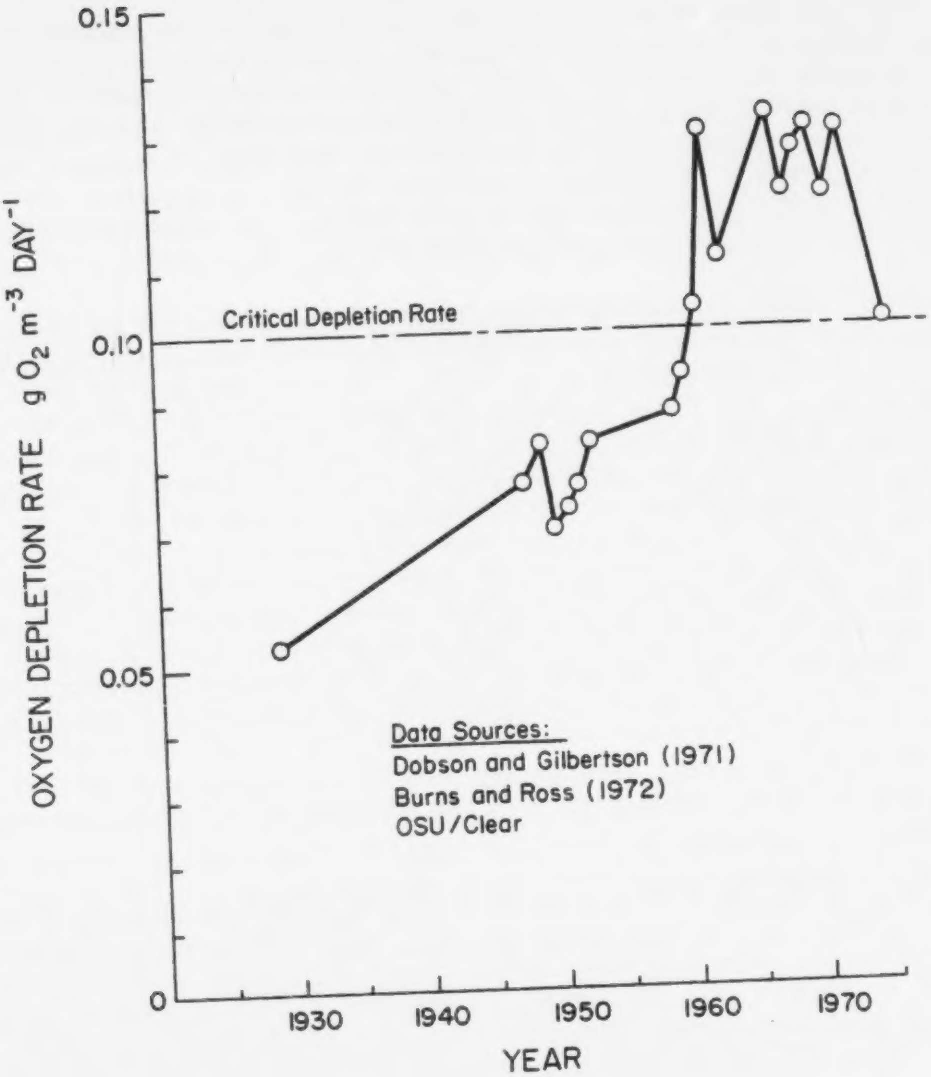

Figure 38. Mean volumetric dissolved oxygen depletion rate for the hypolimnion of the central basin of Lake Erie 1929-1975.

ANOXIA

Factors Influencing Anoxia

Over the last 45 years, the average oxygen concentration of the bottom waters of the central basin have consistently been found to be approximately 10 ppm at the onset of stratification. Based on this fact and a stratification period greater than 100 days, Dobson and Gilbertson (1972) suggest a critical depletion rate of 0.10 $g \cdot O_2 \cdot m^{-3} \cdot day^{-1}$ as causing areas of the basin to become anoxic. This value was exceeded in 1961, however, the central basin may have experienced varying degrees of oxygen deficiencies since 1929.

Carr (1962), in summarizing the available data 1928 - 1961, considered dissolved oxygen concentrations of less than 1.0 ppm as indicative of severe oxygen depletion. Later, in reporting hypolimnetic conditions in 1964, the Federal Water Pollution Control Administration (1968) used a value of 2.0 ppm or less to indicate an oxygen deficit zone of 7500 km^2 in the central basin. However, Piersall and Mortimer (1939) noted ferrous iron (regenerated form) appeared in the sediments of Blelham Tarn at oxygen concentrations of 0.5 ppm, while Burns and Ross (1972) found soluble reactive phosphorous regenerated in the central basin at about the same value. Using values obtained 1.0 m above the bottom (this horizon was selected to prevent disturbing bottom sediments) the regeneration of soluble reactive phosphorous was observed at values between 0.25 and 0.50 ppm oxygen. Therefore, a value a 0.50 ppm has been selected as defining anoxic conditions. This conservative value, considering the sampling horizon, probably represents a higher value than that experienced at the sediment-water interface.

The size of the anoxic area is logically based on several interrelated factors, (1) oxygen depletion rate, (2) stratification characteristics (period of stratification, initial dissolved oxygen content, hypolimnetic exchanges and horizontal movements of bottom waters) and (3) meterological conditions. Because of a lack of data early in 1973, comparisons will be limited primarily to the 1974 and 1975 field years.

Average basin concentrations of 0.3, 0.7 and 3.3 ppm were recorded in late August to early September of 1973, 1974 and 1975, respectively. This was also found to be the time of maximum anoxia and probably represented a stratification period of less than 100 days. Although the average oxygen concentrations were about equal in June of 1974 and 1975 (9.9 and 10.0 ppm, respectively), the total mass of dissolved oxygen in the hypolimnion was initially 137 × 10^6 kg O_2 greater in 1975, and at turnover, it was approximately 182 × 10^6 kg O2 (Table 19). The difference in oxygen content at the onset of stratification can apparently account for 98 percent of the adjusted difference observed between the two years, while the difference due to losses by physical processes amounted to less than 1 percent. Thus, oxygen removal by biological and chemical means was about equal at 8.25 × 10^6 kg $O_2 \cdot day^{-1}$ in 1974 and 8.29 × 10^6 kg $O2 \cdot day^{-1}$ in 1975.

Hutchinson (1957) cited the importance of both exposure and windiness in determining the thickness of the epilimnion. Thus, wind stress (therefore wind velocity) and direction are important variables in the amount of mixing (as indicated by hypolimnetic warming) between the epilimnion and hypolimnion and the relative thickness of both layers. In June 1975, the hypolimnion was approximately 1.5 m thicker and 2.25°C colder than values measured in 1974. This relationship remained throughout the season with 1975 values reaching turnover at 2.3 m thicker and 3.6°C cooler than 1974 estimates (Figures 30 and 31). The initial oxygen content has been suggested as a possible critical factor in anoxia. However, had meteorological conditions been similar to 1974, a greater amount of oxygen would have been removed by physical means resulting in a thinner and warmer hypolimnion.

Over the stratified period May through September the persistence (Figure 39) and mean monthly resultant wind velocities for 1975 are lower, except for the month of July, than values recorded in 1973 and 1974 (Figure 40). The percentage of southwest and northeast winds (axis of longest fetch) greater than 10 mph was 27 percent lower during the 1975 stratified period than resultant velocities in 1973 and 1974. Average velocities neglecting direction in 1975 were lower over the period May through July than the comparable period in 1973 and 1974. Banks (1975) suggested a value of 12.7 mph as the dividing line between strong and light winds. Of the years examined, only May 1975 had markedly fewer number of days with an average daily wind velocity greater than 12 mph (Figure 41). Indeed, the stratified period in 1975 experienced three storms with velocities greater than 24 mph, while none occurred in 1974. As evidenced by volume estimates and temperature profiles, these storms failed to mix the thermocline to a depth equal to that recorded in 1974. Hunt (1954) observed for a given wind speed that the shear stress varied as a function of the difference between the air temperature (Ta) and the surface water tem-

TABLE 19. HYPOLIMNETIC OXYGEN CENTRAL BASIN OF LAKE ERIE 1974 AND 1975 VALUES = kg O2 × 10^6

	1974	1975	Difference (1975–1974)
O_2 conc. at onset of stratification	910.8 (7 June)	1047.7 (12 June)	+136.9
Net O_2 loss due to physical processes	174.7	176.3*	+ 1.6
O_2 depleted by biological* and chemical processes	701.4 (85 days)	654.9 (79 days)	
O_2 remaining at turnover	34.7	216.5	181.8
Adjustments	0	-42.8**	- 42.8**
O_2 conc. diff. 1975–1974 at onset of turnover	34.7	173.7***	139.0
		136.9	136.9
	34.7	36.8	+ 2.1

* O_2 removal at average season rate of 8.25×10^6 kg O_2day^{-1} in 1974 and 8.29×10^6 kg $O_2 \cdot$day^{-1} in 1975.

** 6 days at 11 AN, Average 1975, June removal rate of 7.13×10^6 kg O_2day^{-1}.

***Adjusted 1975 O_2 remaining at turnover.

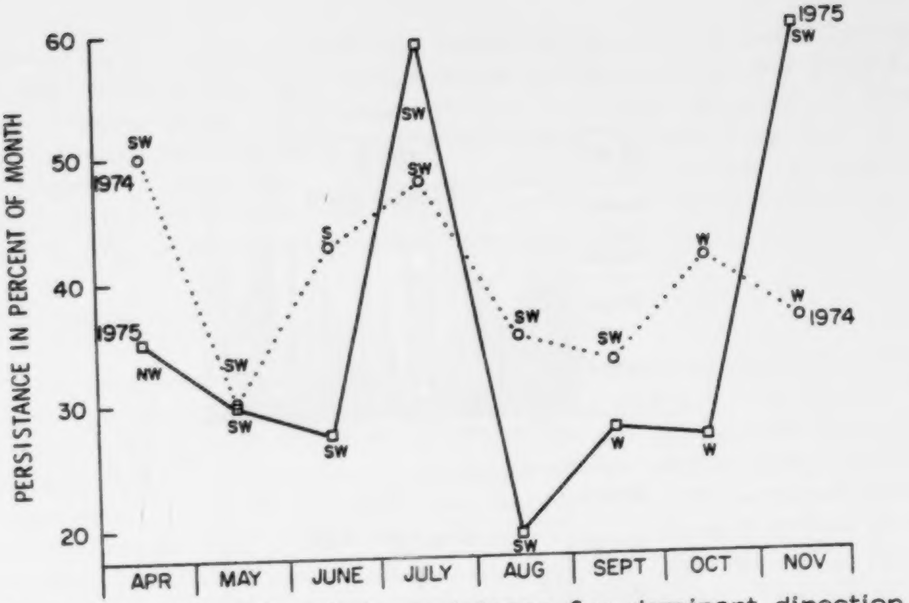

Figure 39. Monthly wind persistence for dominant direction at Long Point, Ontario for 1974 and 1975.

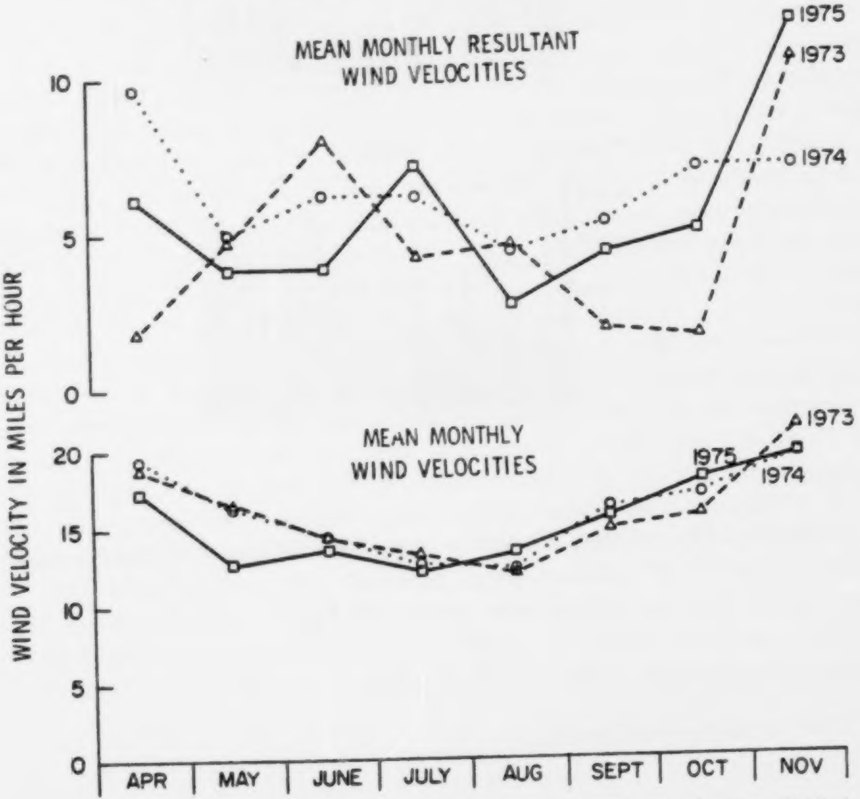

Figure 40. Average and resultant winds at Long Point, Ontario for 1973-1975.

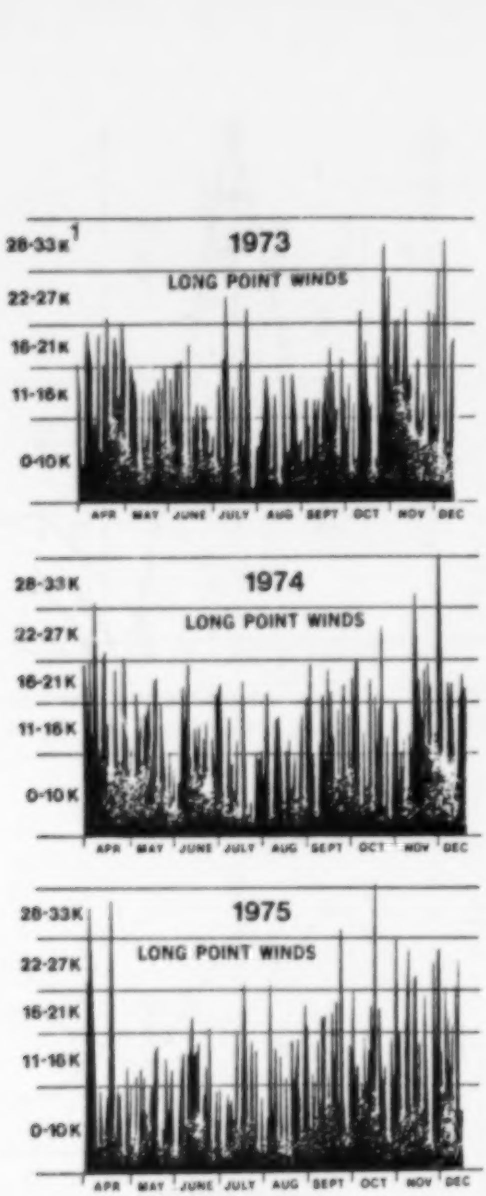

Figure 41. Long Point winds for 1973, 1974 and 1975.

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[1] "K" stands for knots.

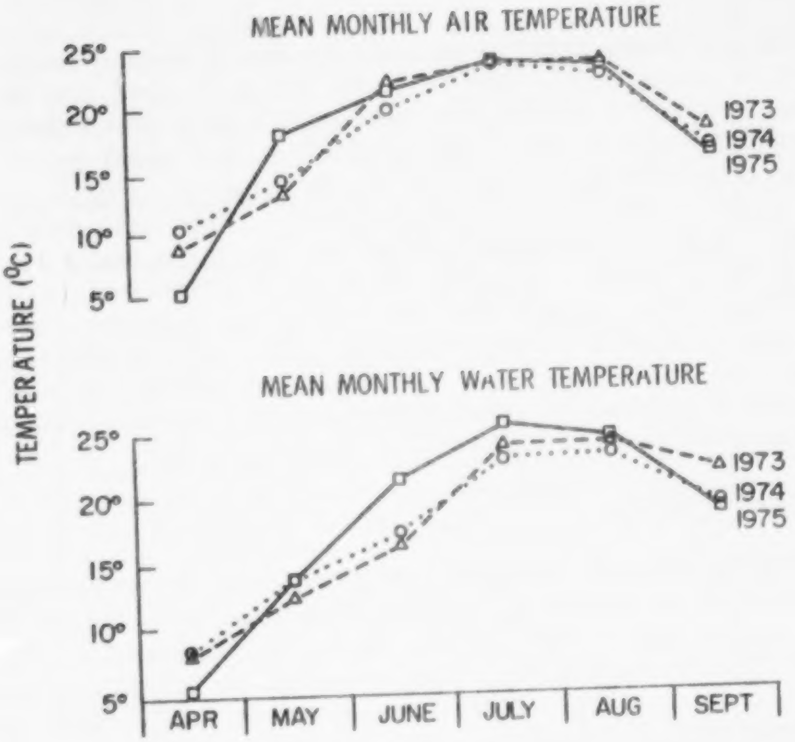
perature (T_W). Although surface water temperatures were higher in 1975, the monthly average temperature difference for the stratified season, as measured at Marblehead (Table 20), was smaller in 1975 with all three years indicating a stable to neutral atmosphere for the stratified season (Figure 42). Since the given time frame is lengthy, the role of the air-water temperature difference is somewhat inconclusive as to its effect on the 1974-75 hypolimnia.

Central Basin Anoxia

The first comprehensive survey of the central basin (June-September) was performed in 1929 by Fish et al. (1960). The lowest recorded oxygen value was 4.4 ppm at a station 25 miles northwest of Cleveland, Ohio. This value was noted about mid-August, while the next survey did not occur until mid-September (temperature contours indicate turnover had occurred by this time). Stratification in this basin usually persists from late May or early June to early or mid-September, depending on meteorological conditions. The time of maximum areal extent of anoxia was found to be late August to early September in 1973-1975. Thus, Fish et al. (1960) had probably missed the ideal time for perception of anoxic conditions. Also water samples taken 1.0 m above the bottom were not always taken below the metalimnion. Fish's (1929) study, as in many subsequent surveys, failed to sample the southwest portion of the basin. This area, roughly bounded by the triangle formed by Sandusky, Ohio to Lorain, Ohio to Pelee Point, Ontario, is historically the most consistent area of anoxia, with anoxia usually starting in this area and spreading to other portions of the basin. In 1973-1974, it was found also to be an area with a thin and transitory hypolimnion. In August 1930, Wright (1955) recorded an oxygen value of 0.8 ppm at a station 1.1 km east of Marblehead Light. However, more eastward stations sampled on the same day were well oxygenated. This reading, although on the extreme western edge of the central basin, probably represented a transitory situation such as that experienced in the western basin. Studies by the University of Western Ontario failed to show any anoxic conditions during the period 1947-1953, and low values of 2.1 and 2.0 ppm were noted in mid-lake and off Rondeau Harbor, Ontario (Powers 1960). In 1959 and 1960, federal, provincial, state and university organizations participated in determining the extent of low dissolved oxygen waters in the central basin (Beeton 1963). These studies revealed an area of 3,600 km^2 in 1959 and 1,660 km^2 in 1960 with hypolimnetic oxygen

TABLE 20. MONTHLY AVERAGE AIR-WATER TEMPERATURE DIFFERENCE (°C) - MARBLEHEAD AND PUT-IN-BAY, OHIO

	1973	1974	1975
April	+1.6	+2.6	+0.5
May	+0.9	+0.6	+4.5
June	+5.6	+2.7	+0.1
July	-0.9	+0.3	-2.1
August	-0.8	-0.8	-1.1
September	+0.1	-2.3	+0.0


MEAN MONTHLY AIR TEMPERATURE

MEAN MONTHLY WATER TEMPERATURE

Figure 42. Mean monthly water temperatures at Marblehead, Ohio for 1973-1974.

Note: July-September, 1973 values estimated from Put-in-Bay, Ohio records.

values less than 1.0 ppm (in 1959 the area with less than 0.5 ppm oxygen was 780 km^2). Subsequently, every year sampled (Carr, 1962; Great Lakes Institute, 1964, 1965; Canada Centre for Inland Waters, unpublished data 1967-1970) has shown anoxic areas, but due to sampling patterns, accurate estimates of the areal extent of this condition were not possible.

Burns and Ross (1972) indicated an anoxic region (zero percent saturation) of about 6,600 km^2 in 1970, while in 1973 and 1974 maximum areas of 11,270 and 10,250 km^2 ($<$0.5 ppm dissolved oxygen) were recorded. However, in 1975, although the areal depletion rate was at the critical value of 0.10 g $O_2/m^{-3} \cdot day^{-1}$, only about 2.5 percent (400 km^2) of the basin became anoxic. This indicates the dramatic fluctuations (63.4 to 2.5 percent) that can occur in the anoxic area of the central basin between years. An accurate comparison of the anoxic area is difficult and can be obscured by station patterns, sampling times, length of stratification, meteorological effects and horizontal movements of hypolimnetic waters. Also, the transitory nature of anoxia in the southwestern portion of the basin further confuses the extent of oxygen-deficient waters.

Western Basin Anoxia

Carr et al. (1965) estimated that five days of stratification were required in 1963 to reduce oxygen concentration of portions of the western basin to 3.0 ppm, whereas, 28 days were needed in 1953. During a period of light winds, Britt (1955) reported an oxygen concentration of 0.1 ppm at a stratified station two miles west of South Bass Island. He associated this observation with a large reduction in the mayfly (*Hexagenia* sp.) population of this area. Later, Britt et al. (1968) reported (for the same area) a drop from 3.0 to 0.1 ppm (10-15 cm above the bottom) over the five-day period 26 June to 1 July, 1966. Two cruises (Figures 43-44), 10-12 July and 29-30 August, in 1973 obtained values of less than 3.0 ppm for a sampling horizon 1.0 m one meter above the bottom. At these stratified sites, the dissolved oxygen concentration rapidly fell below 1.0 ppm as the sensor neared the bottom. These areas of low oxygen were west and north of the sites sampled by Britt (1953). Additionally, unusually large quantities of silica, ammonia and phosphorus were observed in the western basin on 20-21 July 1975. Although oxygen values ranged between 6 and 9 ppm at the time of the cruise, the presence of these nutrients indicates a probable regeneration due to a prior anoxic condition.

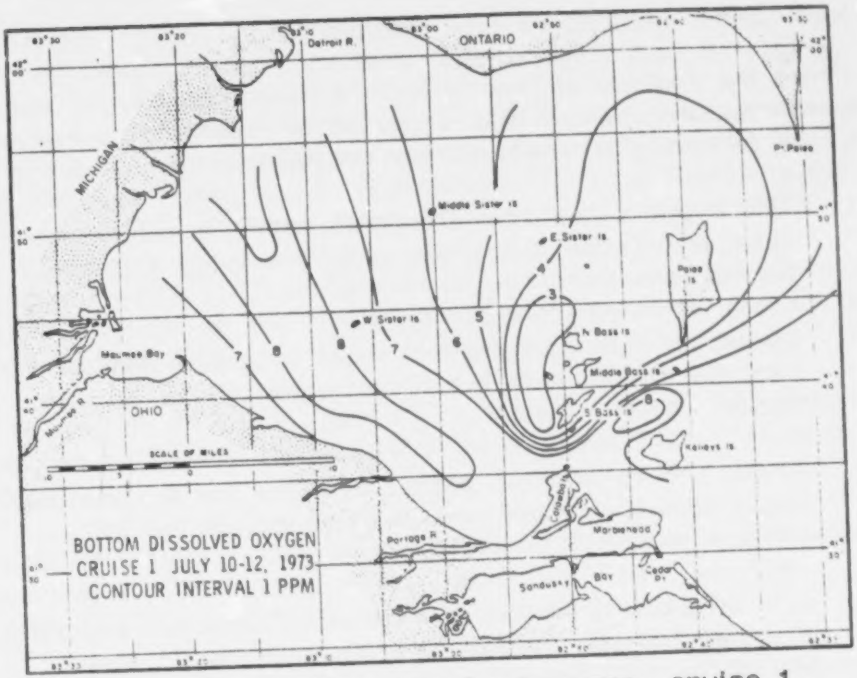

83°20
83°10
Detroit R.
83°00
ONTARIO
82°50
MICHIGAN
Pt. Pelee
Middle Sister Is
E. Sister Is
Pelee Is
W. Sister Is
N. Bass Is
Middle Bass Is
S. Bass Is
Kelleys Is
Maumee Bay
Maumee R.
OHIO
SCALE OF MILES
Portage R.
Catawba Is
Marblehead
Sandusky
Bay
Cedar Pt.
BOTTOM DISSOLVED OXYGEN
CRUISE 1 JULY 10-12, 1973
CONTOUR INTERVAL 1 PPM
7
8
8
7
6
5
4
3
8

Figure 43. Bottom dissolved oxygen, cruise 1, July 10–12, 1973.

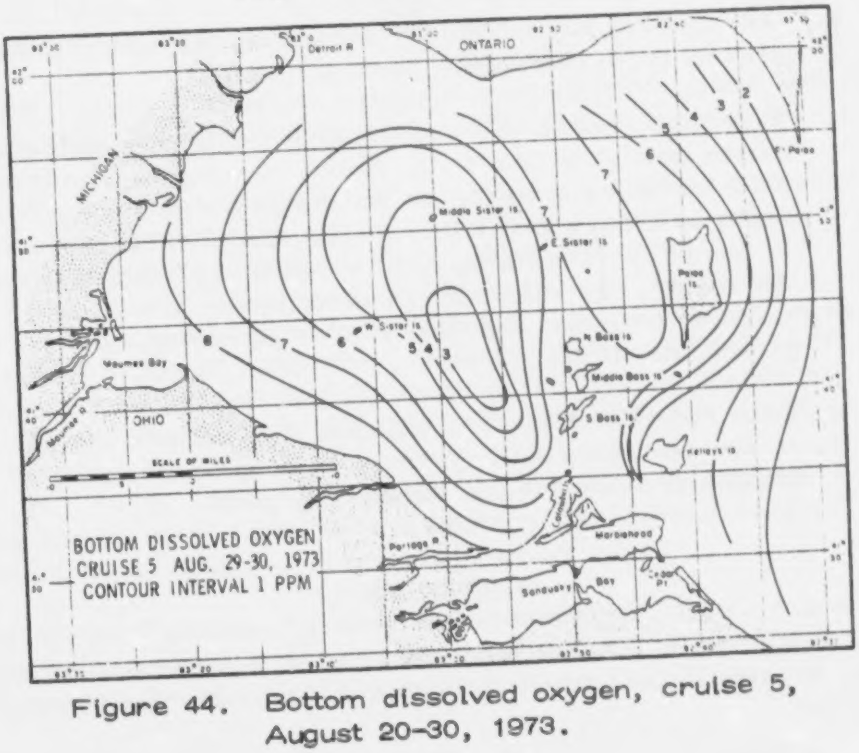

83°20
Detroit R.
ONTARIO
82°50
82°40
MICHIGAN
Pt. Pelee
Middle Sister Is
E. Sister Is
Pelee Is
W. Sister Is
N. Bass Is
Middle Bass Is
S. Bass Is
Kelleys Is
Maumee Bay
Maumee R.
OHIO
SCALE OF MILES
Portage R.
Catawba Is
Marblehead
Sandusky
Bay
Cedar Pt.
BOTTOM DISSOLVED OXYGEN
CRUISE 5 AUG. 29-30, 1973
CONTOUR INTERVAL 1 PPM
2
3
4
5
6
7
7
8
7
6
5
4
3

Figure 44. Bottom dissolved oxygen, cruise 5, August 20–30, 1973.

CONCLUSIONS

From the results of the 1973-1975 dissolved oxygen surveys of the central and western basins and a review of historical surveys of these basins, the following conclusions are extracted:

1. The hypolimnion of the central basin is subject to relatively large exchanges with overlying and adjacent waters.

2. Depletion rate calculations must estimate and correct for fluxes with the hypolimnion of the eastern basin.

3. Areal and volumetric depletion rates for the central basin show no improvement over the period 1973-1975.

4. The volumetric depletion rate has fluctuated around a value between 0.12-0.13 g $O_2/m^{-3} \cdot day^{-1}$ since the early 1960's and has not fallen below the "critical rate" of 0.10 g $O_2/m^{-3} \cdot day^{-1}$ since this time.

5. The central basin can be classes as eutrophic based on the 1973-1975 areal depletion rates.

6. Potentially large fluctuations (63.4-2.5 percent between years) in the areal extent of annoxia eliminates this factor as a criterion for judging the trophic state of the central basin. The usefullness of this criterion is limited by lack of accurate historical estimates, the difficulty in determining the maximum extent, and the effects of meteorological conditions limit.

7. Data for 1973 and 1975 indicate that bottom waters in the western basin continue to become depleted of oxygen and experience temporal anoxia.

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SECTION 4

TRANSPARENCY, CONDUCTIVITY AND TEMPERATURE SURVEYS IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

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INTRODUCTION

Transparency and conductivity surveys were conducted in the central and western basins of Lake Erie for 1973 through 1975. A 30-cm black and white Secchi disk was used to determine transparency by lowering it on a marked line into the water until it disappeared from sight. This depth is termed the Secchi depth. Specific conductance and temperature were measured with a Martek Mark II Model A _in situ_ monitoring system and recorded in micromhos per centimeter (µmhos/cm) and °C. Prior to each cruise the conductivity meter was calibrated against a standard and batteries were changed.

SECCHI DISK TRANSPARENCY

Values for the area-weighted basin average for the Secchi depth transparency are presented for the years 1973 through 1975 (Figure 45). Except for 1973, these data were recorded during the period April to December in both the central and western portions of Lake Erie. Although 1973 values are presented, they are not included in the following discussion due to the shortness of the observation period (July-November). The area-weighted averages are presented as Secchi depth reciprocals as an indicator of particulate matter (Vollenweider, 1960; Postma, 1961) to effect a comparison with similar data collected earlier (1969-1971) by the Canada Centre for Inland Waters (Dobson et al. 1974).

Secchi values (this study and Dobson et al. 1974) demonstrate a gradual increase in depth (decrease in surface particulates) from April

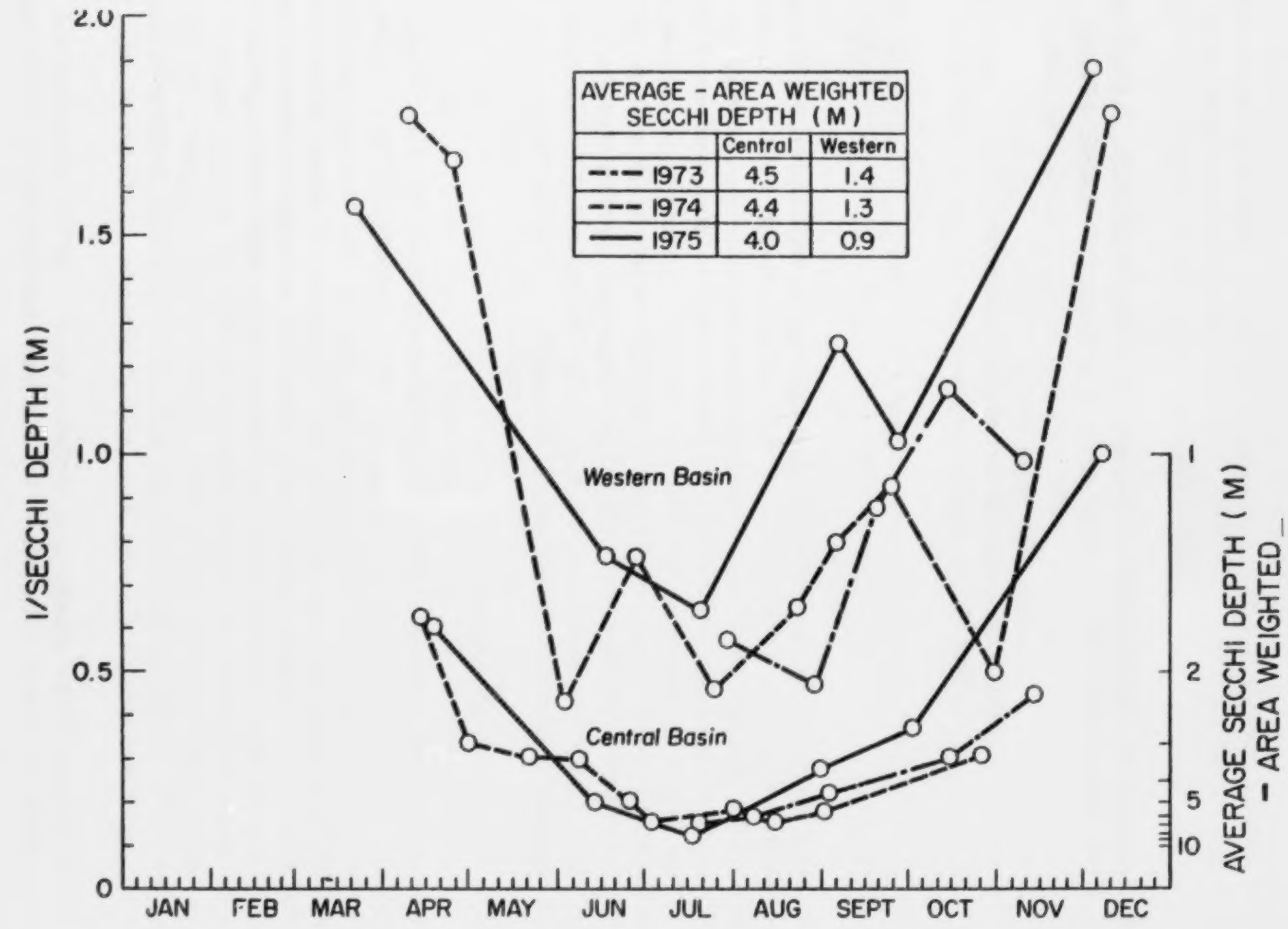

Figure 45. Average area weighted Secchi depth for the central and western basins of Lake Erie.

through July, followed by decreasing values into December (Figure 45) in both the central and western basins of Lake Erie. Pinsak (1967), using an in situ turbimeter, reported a 50 percent increase in suspended material in the central basin (July-November). He attributed the increase to a seasonal increase in organic material, movement of water from the western basin, turbulent storm effects and vertical circulation of the entire water column at turnover. The latter two effects are well demonstrated in Figure 45. A sampling of the central basin before and after a strong northeast storm showed a reduction of the Secchi depth by 1-3 m. Influences of the western basin are readily apparent by distribution patterns which place shallow Secchi depths at the west and southwest portion of the central basin. Secchi depths, when taken as a yearly average, are approximately 3 m deeper in the central basin than in the western basin.

The average yearly value for both the central (4.4 m) and western (1.3 m) basins was 0.4 m greater in 1974 than in 1975 (even though a peak value of 8 m was recorded in July 1975). Precipitation in the Great Lakes basin was significantly greater in 1975 than in 1974 (Figure 46); likewise, rainfall in the Lake Erie basin was 4.8 inches greater in 1975 than in 1974 and 5.11 inches greater than the previous 75-year average annual rainfall (Figure 47). The month of August was 4.32 inches greater than the 75-year average monthly rainfall for August.

Central Basin

Cruise peak values (July) of 6.7 m, 6.3 m and 8.0 m (3-year mean value, 7 m) obtained from 1973-1975 respectively, show a deeper Secchi depth (less particulates) than a July peak value of 5 m for 1969-1971 (Dobson et al. 1974). When plotted, cruise contours show a yearly range of values of 1 to 13 m in the central basin. Generally, shallower values are found in the southwest portions of the basin and along the south shore. Larger Secchi depths were obtained in mid-lake areas often with one or two lenses of high surface transparency in the eastern and western portions of the central basin.

Western Basin

The western basin also experiences peak values during July; however, fluctuations appear more marked (due in part to the reciprocal nature of graph) and are of greater frequency. This basin is subject to higher direct inputs of particulates from tributaries, and due to its shallow nature (mean depth, 8.5 m), is subject to frequent resuspensions. As presented elsewhere, 1975 was characterized meteorologically as

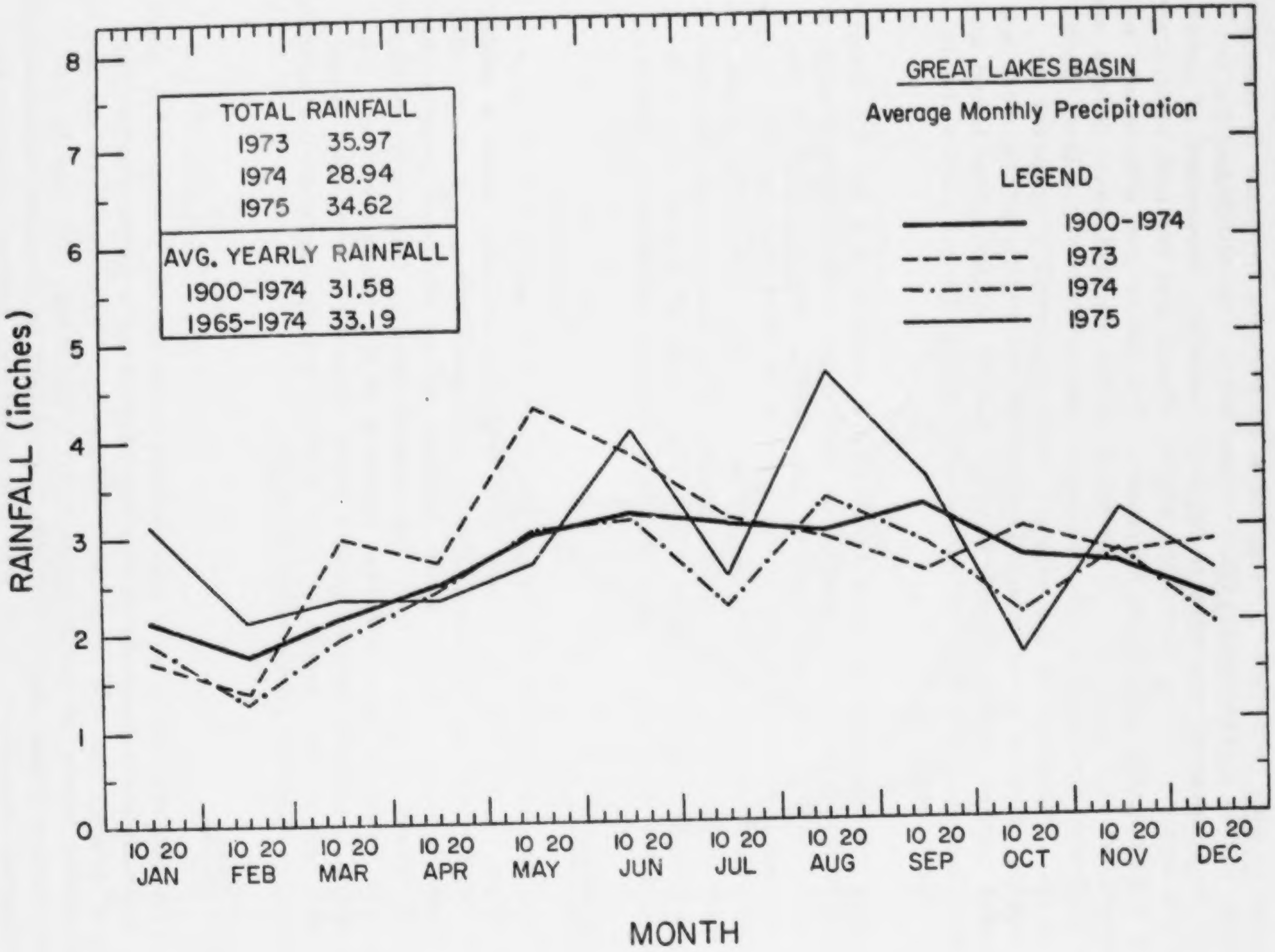

Figure 46. Great Lakes basin average monthly precipitation.

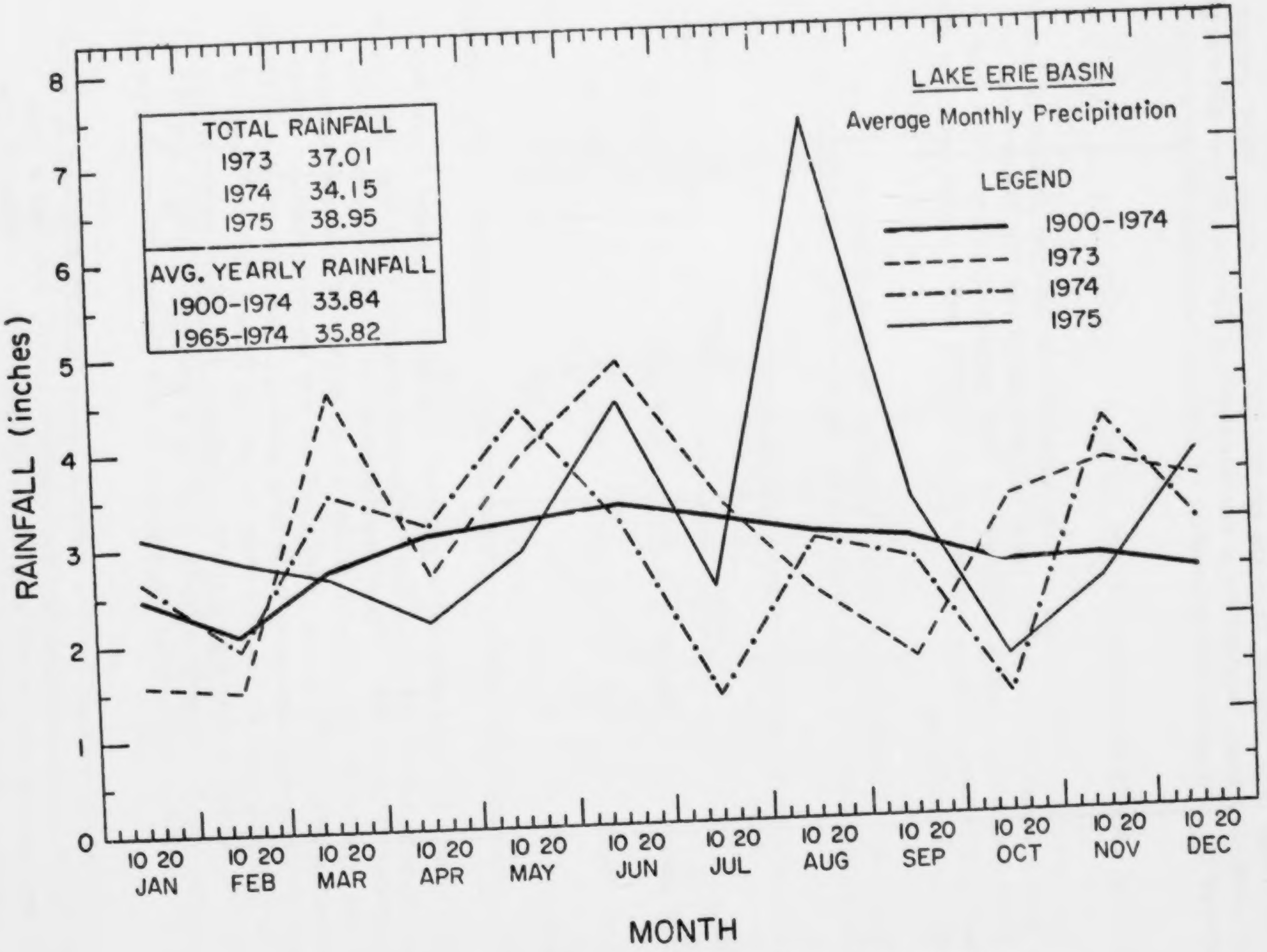

Figure 47. Lake Erie basin average monthly precipitation.

having lower wind velocities, a marked change in dominant wind direction, and high surface water temperatures relative to 1973 or 1974. All of these phenomenon impinge on column mixing; thus, 1974 values have probably been subject to a combination of Detroit River discharge modified by a greater resuspension of bottom materials (Figure 48).

SPECIFIC CONDUCTANCE (TOTAL DISSOLVED SOLIDS)

The specific conductance of the western and central basins of Lake Erie was normalized to 25°C, then volume-weighted for 10 cruises in 1974 (April-October) and 6 cruises in 1975 (March-December) (Table 21). Surface and bottom contour maps for 1973-1975 were constructed to show distributional patterns.

TABLE 21. SPECIFIC CONDUCTANCE IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE, 1974 - 1975, (UMHOS/CM)

Year / Basin	1974	1975	Difference
Central Basin	291.32 ± 9.72	266.0 ± 16.94	25.32
Western Basin	259.89 ± 8.10	227.23 ± 24.05	32.66
Difference	31.43	38.77	

The trend in 1975 showed a gradual decrease in values from April to late August after which values increased sharply until the last cruise in December (Figure 48). The International Joint Commission (IJC, 1975) has identified the Detroit River as a source of low conductance water that exerts a "flushing principle" on the western basin. They suggest an apparent decrease in yearly average conductivity from 1966-1973 as possibly due to an increase in yearly flow (1320 m^3/sec) of the Detroit River during this period. Indeed, the 1974 western basin conductance values showed a good inverse relationship (Figure 49) implying a modifying parameter in addition to the Detroit River discharge.

Conductivity values for the central basin in 1975 followed a trend similar to that demonstrated for the western basin, but had a less marked decreasing and increasing slope (Figure 49). Values in the central basin in 1974 showed a decrease only from June through late

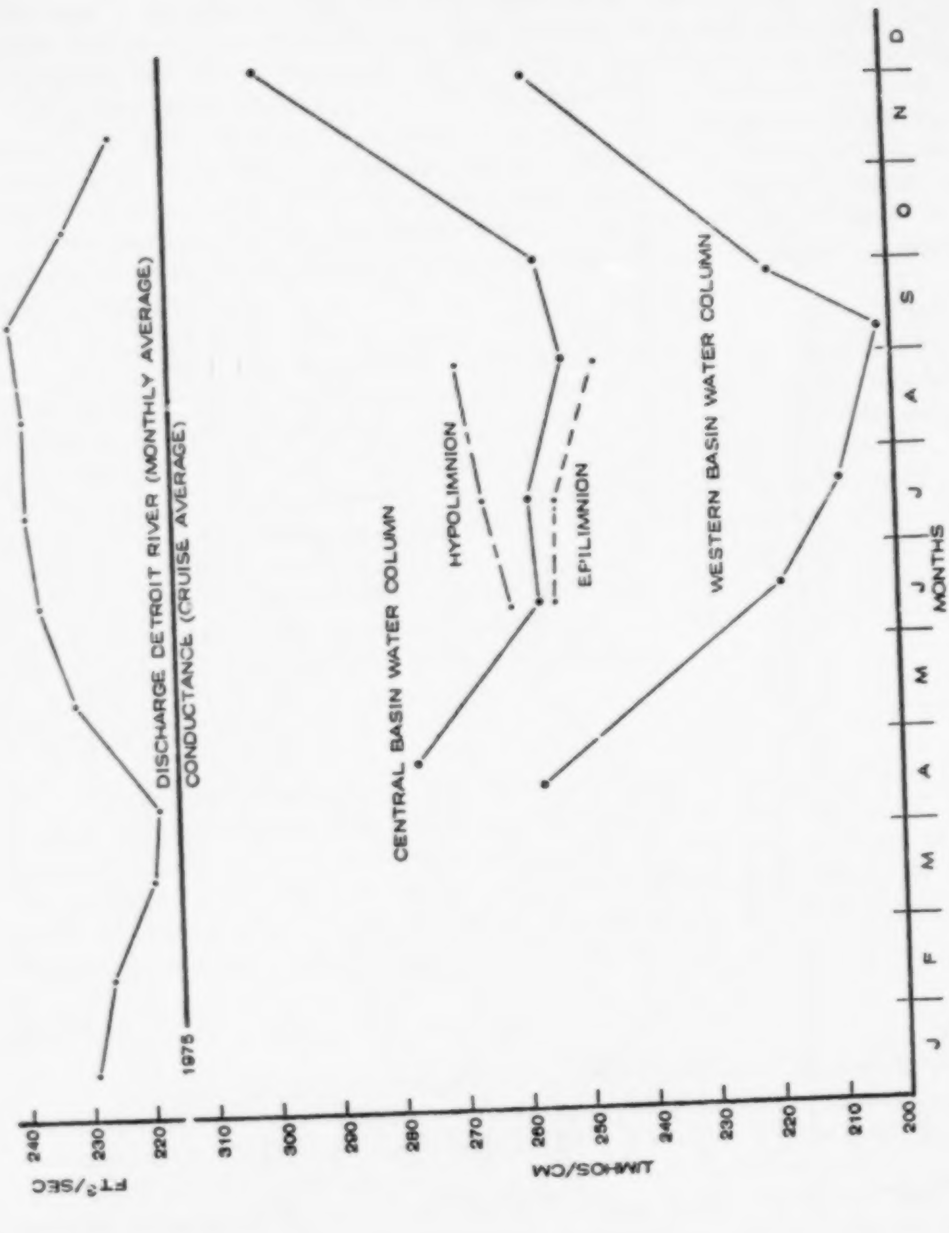

Figure 48. Specific conductance in Lake Erie 1974.

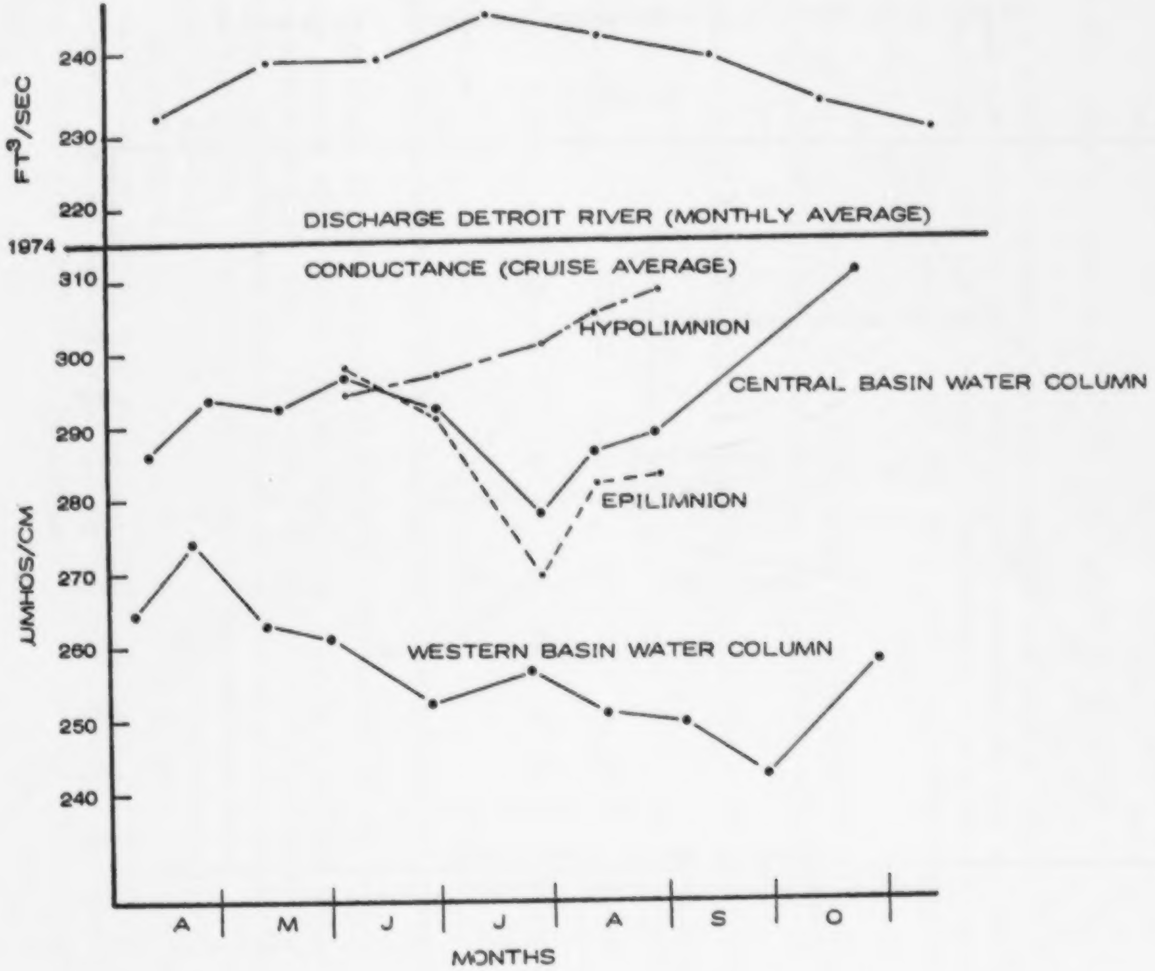

Figure 49. Specific conductance in Lake Erie 1975.

July, while values in the western basin for the same year showed a decrease from April-September. Generally, the only apparently consistent pattern in the central basin for both years was that basin values decrease in late spring and increase from early fall through December. The entire water column average closely followed the epilimnion concentrations, while average hypolimnetic values increased almost linearly during the stratified portion of the season (+ 0.16 and + 0.13 µmhos/ day^{-1} in 1974 and 1975, respectively). The greatest influence of epilimnion concentration was apparently due to the high epilimnetic volume (65-75 percent of entire column) relative to the hypolimnetic volume. Higher conductivities are recorded in the central basin than in the western basin, an average of 31 and 39 µmhos greater in 1974 and 1975, respectively.

In both 1974 and 1975, average values of 291 and 266 µmhos for the central basin and 260 and 227 µmhos for the western basin were recorded. These yearly values for the basin were within the IJC recommended level of less than 308 µmhos (Figure 50). However, the U.S. Army, Corps of Engineers (1975) reported that 67.5 percent of the total 1975 phosphorus loading into Lake Erie occurred from January through March. Assuming the bulk of conductive materials entering the lake are loaded at the same time, then the values reported here are on the low side when compared with earlier data which may have been biased by nearshore measurements.

TEMPERATURE

Seasonal changes in air temperatures (Figures 51 and 52) and water temperatures were similar for the first two years of the study. Dramatic changes in the meteorological conditions in 1975 are discussed in the Overview, Dissolved Oxygen and Winds sections of this report. The following discussion of water temperature in 1974 represents typical seasonal trends which occur in Lake Erie.

Surface 1974

Surface temperatures in early April showed a spring warming trend in the western basin and along the Ohio shore, particularly influenced by the Maumee River. The Ontario shore and the northeastern part of the central basin were the coolest areas (2°C), a situation which persisted for several months. By early May the western basin had warmed to 10°C and the cool part of the central basin was up to 6°C. The temperature differential was still evident in early June with a greater than 6°C rise from the northeastern to the southwestern portion of the central basin. By mid-August the two basins were very

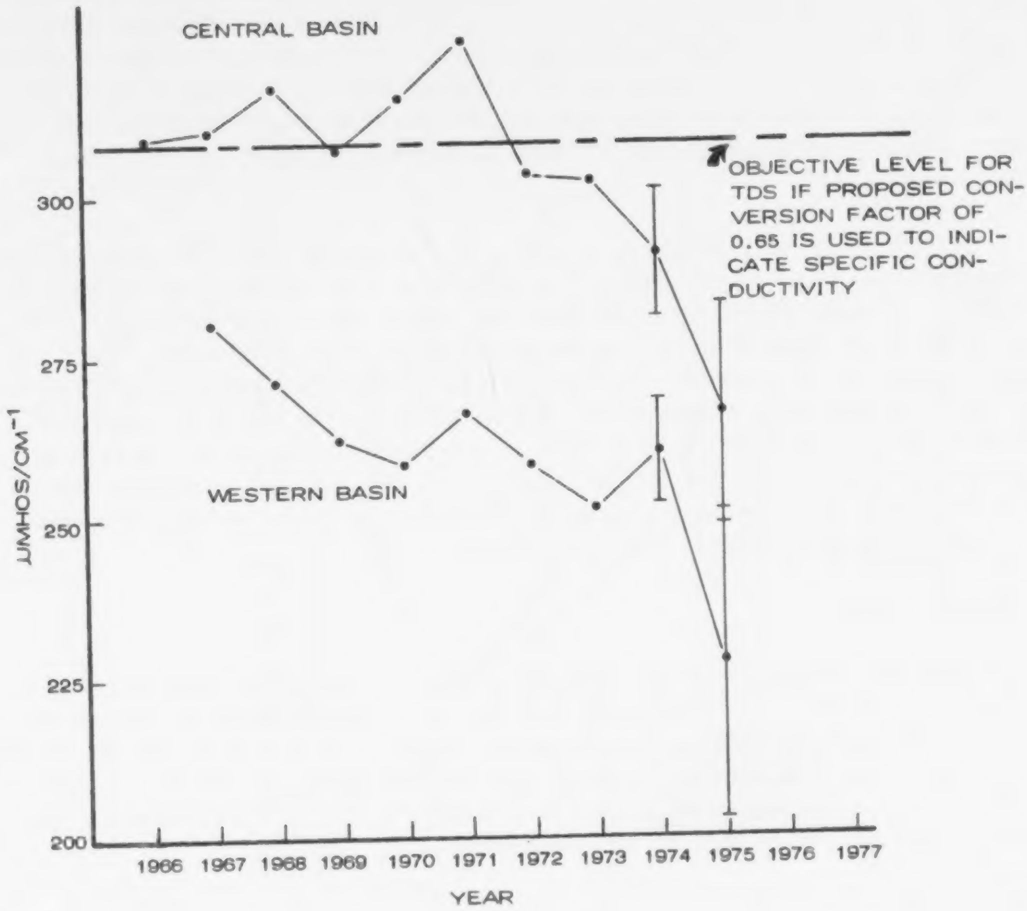

Figure 50. Specific conductance in Lake Erie.

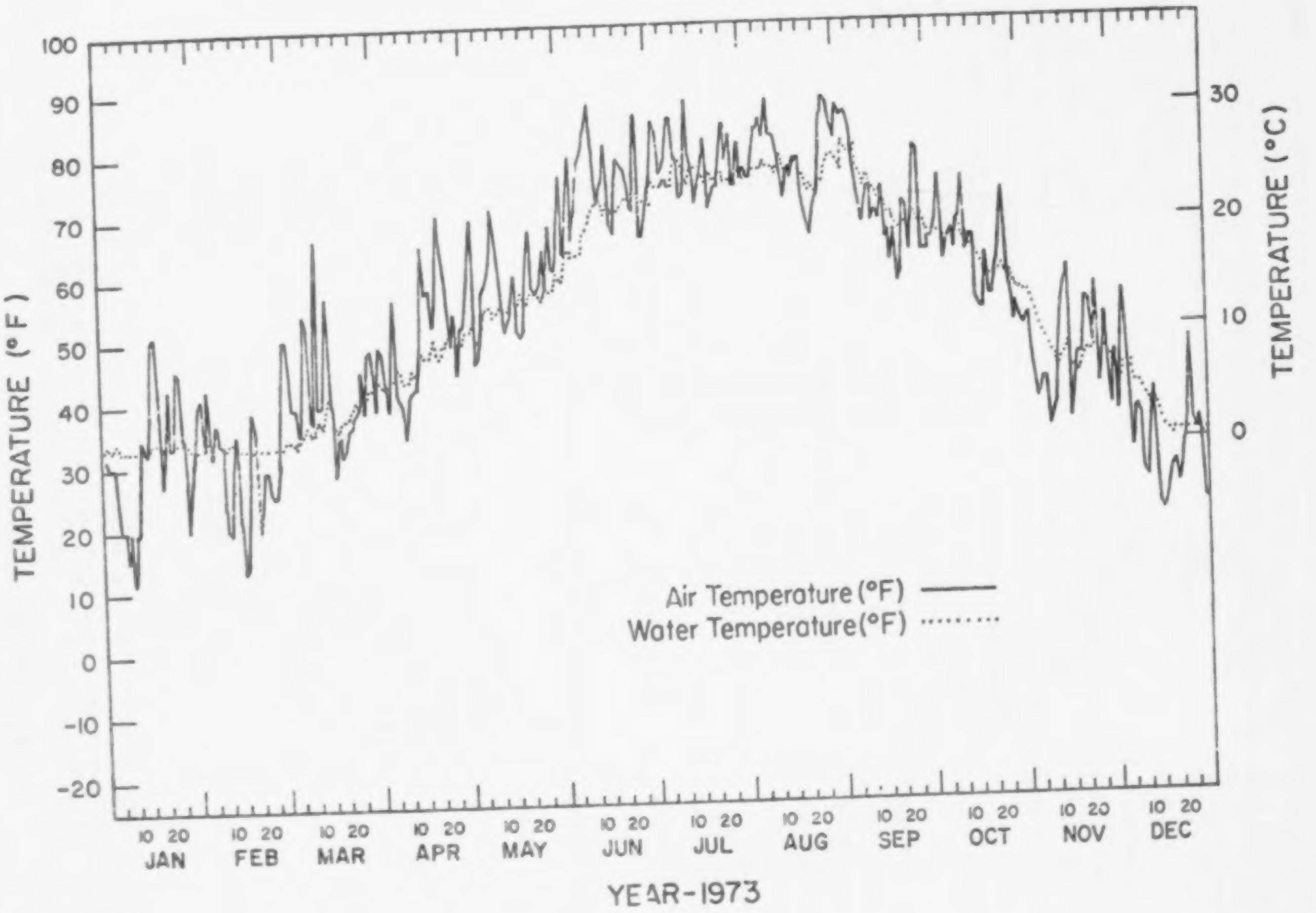

Figure 51. Air and water temperatures at Put-in-Bay, Ohio 1973.

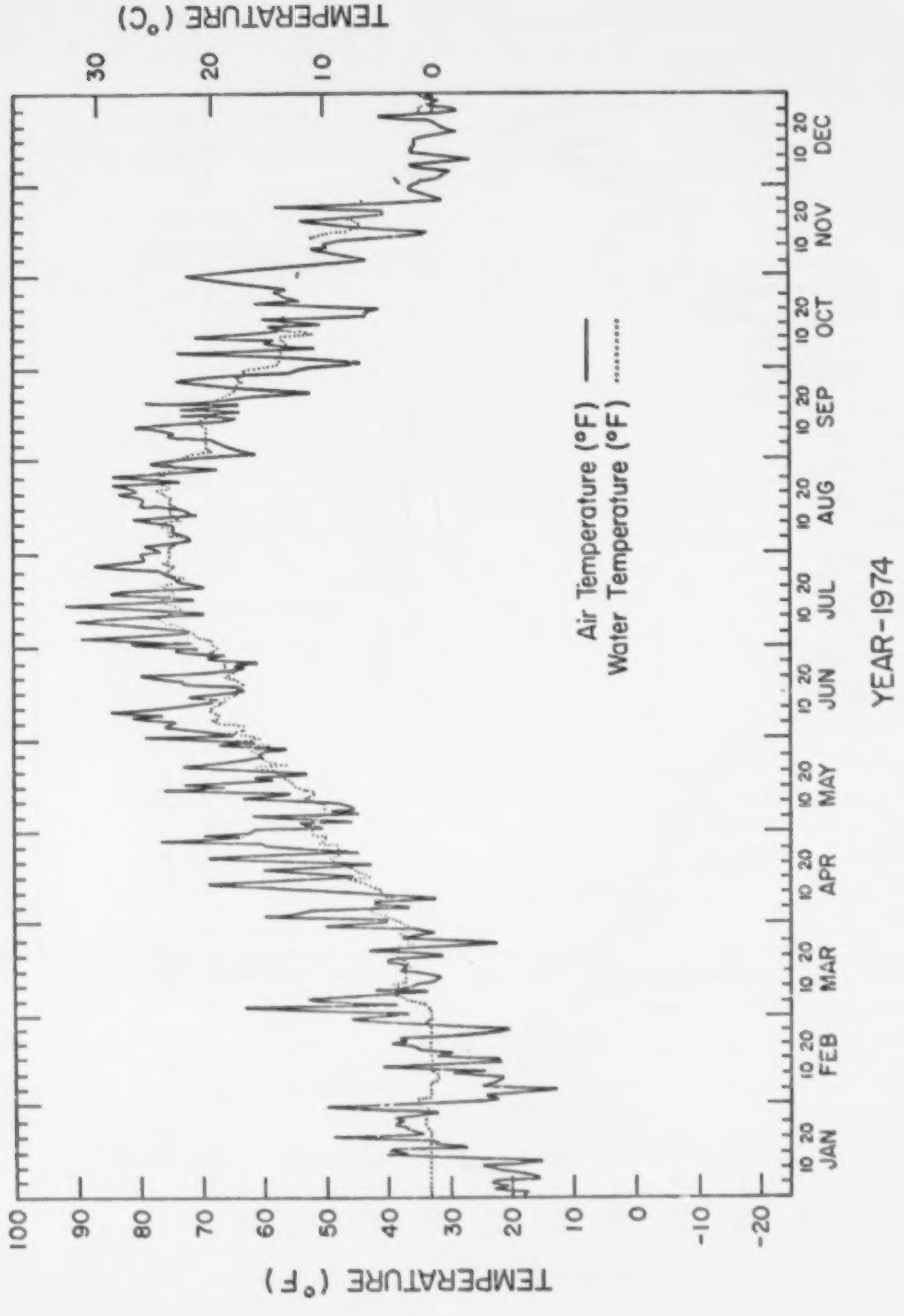

Figure 52. Air and water temperatures at Put-In-Bay, Ohio 1974.

similar in surface temperature with only a 2° range. In early September the cooling of the upper Great Lakes became evident as the Detroit River flow lowered the temperature of the western basin by 4°C. The lake overturned in Mid-September and by late October the surface temperatures were only half of what they were in early September.

Bottom 1974

In early April much of the bottom water in the western and central basins was 4°C at its most dense point. Maumee River flow appeared to be warming the southwestern segment of the western basin. By early May warming was very evident along the Ohio shoreline but was less well developed near the Ontario shore. The bottom temperature of the western basin doubled while the central basin showed a much smaller rise, reflecting the stratification that had taken place in that basin. This is also apparent from the surface temperature map for early June. In mid-August the bottom water reached its greatest degree of warmth and by early September the western basin and the nearshore (unstratified) areas of the central basin had cooled considerably. The deeper portion remained between 12°-14°C until turnover in mid-September. In late October the two basins were nearly isothermal and ranged between 10°C-12°C.

CONCLUSIONS

From the survey of these three parameters, the following can be concluded:

1. Secchi values for both the central and western basins showed a gradual increase in depth from April through July and August and a general decrease in depths thereafter. This phenomenon is more apparent in the central basin which, over the shipping season, showed deeper measures than the more variable western basin.

2. In the central basin cruise peak values for 1973-1975 were greater than the average peak values for 1969-1971.

3. Cruise peak values for the western basin for 1974-1975 were similar to the peak average values obtained by Dobson et al. (1974) for the period 1969-1971.

4. For the period April-December 1974, average conductance values in the western and central basins fell below the IJC criterion of 308 umhos.

5. The western basin conductance values apparently vary inversely to the Detroit River discharge, a relationship probably modified by wind-induced mixing.

6. Central basin conductance values are usually higher than western basin values and follow a general pattern of values decreasing in late spring and increasing from September through December. Hypolimnetic values increase linearly, while epilimnion values are more subject to fluctuations.

7. The central basin of Lake Erie is isothermal throughout winter and early spring with stratification occurring in late May or June.

8. Central basin stratification persists for approximately 100 days with overturn generally occurring in September.

9. Because of its shallow depth, the western basin rarely stratifies and when it does it is for only short periods of time.

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SECTION 5

LAKE ERIE WINDS: A PRELIMINARY ANALYSIS
1973-1975

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INTRODUCTION

The ability to estimate accurately the wind field over Lake Erie is necessitated by the fact that seiches, currents, and waves on the lake are directly related to over-lake wind field.

The wind blowing over the lake surface produces a rhythmic short-term oscillation of the lake level called a seiche. Seiche activity on Lake Erie has resulted in differences in water level between Toledo and Buffalo of over 3.5 meters (Platzman, 1963). Abnormal low water levels can seriously hinder navigation near the Detroit River or power production on the Niagara River. Gillies (1959) notes that a 0.93 meter drop in lake elevation at Buffalo can reduce potential electrical energy generation on the Niagara River by 1200 megawatts.

The wind-generated currents at the surface can influence subsurface motion and change the thermal structure of Lake Erie which, in turn, can affect such properties as the degree of oxygen depletion. Currents effect the dispersion of water-borne pollutants and the formation, movement, and dispersion of ice. They are also related to the distribution of such water properties as alkalinity and turbidity. Gedney and Lick (1970) have developed a numerical model based on finite differences which calculates the steady state, wind driven currents in Lake Erie as a function of depth and horizontal position.

Wave characteristics, principally wave height and wave period, are sought for both the average and extreme situations for the planning and construction of adequate yet economical breakwaters which reduce possible erosion or damage to coastal installations. Accurate estimates of mid-lake wave characteristics, associated with a given wind field, are necessary for both commercial and recreational boaters.

Previous Studies

Various methods for estimating the winds have been proposed. Examples of methods applied to Lake Erie are given by Hunt (1959), Lemire (1961), Richards et al. (1966), Barrientos (1971) and Feit and Barrientos (1974).

The number of over-lake wind observations are too sparse or infrequent to be used as the sole determinant of the over-lake wind field. Various investigators (Hunt, 1959; Lemire, 1961; and Richards et al. 1966) have employed the relationship between simultaneously observed over-lake and over-land wind speed observations. They estimate the over-lake wind speed from the computed relationship (R) of the wind speed over water (U_w) to the wind speed over land (U_l) where:

$$R = U_w/U_l$$

R deviates from unity in response to the various influences which cause the wind speed over water to vary from that over the land; i.e.:

1. The difference in frictional effect between land and water,

2. The difference in atmospheric stability induced by air-water temperature differences,

3. The length of the over water fetch.

Examples of R obtained in Lake Erie studies are:

	R(Annual)	R(Spring)	R(Fall)
Hunt (1959)	1.56	1.35	1.82
Lemire (1961)	1.63	1.38	1.87
Richards et al. (1966)	1.66	1.33	1.85

Hunt (1959) and Richards et al.(1966) studied the effects of stability on R while the latter also included the influence of fetch on R. These studies found that:

1. R increases as over-water stability increases.

2. Under stable over-water conditions, R increases as the over-lake fetch increases up to 20 km.

In the aforementioned studies, R was determined by dividing the lake into arbitrary sections such that each section had one land station with which to correlate ship observations. This method lacks rigor since ship observations occur at different locations within these sections; thus, the resulting R is, at best, representative of the entire section, and does not supply information of sufficient density to be useful in assessing spatial variation. A more rigorous approach would be to expand, by interpolation, the observed wind speed values from the land stations to over-lake locations. It could then be assumed that the interpolated values and corresponding ship observations are for the same location on the lake and a single relationship between the observed winds could be determined. This was the method suggested by Barrientos (1971), but instead of using an objective interpolation algorithm he devised subjective equations to reduce land station observations to inferred values representing half the lake, e.g.:

East Erie = 0.25 (Cleveland) + 0.50 (Erie) + 0.15 (Buffalo)

He used this method because the accuracy of the interpolation procedure was not compatable with the other assumptions made. Interpolation could not realistically be used since station input from Canada was lacking, thus only extrapolation could result. In a later study (Feit and Barrientos, 1974) which did use Canadian data, interpolation was used to reduce the land station observations to over-lake locations. For both studies, regression equations were developed to predict the surface winds from forecasted meteorological elements, not just wind speeds. The entire methodology is an improvement over previous studies, but still does not provide sufficient information concerning the spatial variation of the winds.

Study Purpose and Scope

The purpose of this study is to provide useful information concerning the winds over Lake Erie. To provide this information two different objectives were necessary.

All of the aforementioned studies estimate a wind speed, representative of large sections of the lake, based on empirical relationships between simultaneously observed over-lake and over-land meteorological elements. None of these methods provide a rigorous investigation of the spatial variation of the surface winds, i.e., the surface wind field. Therefore, a primary objective is the development of a methodology, using theoretical considerations as well as empirical relationships, to estimate the surface wind field of Lake Erie. Meteorological elements, primarily those recorded at surrounding land stations, but also those from a limited number of concurrent over-lake measurements, are interpolated to a 15-kilometer grid network over Lake Erie. Predictive equations, which reflect empirical and/or theoretical considerations, and which employ the interpolated values of the meteorological elements, are applied at each grid node of the grid network to produce the estimated surface wind field.

The wind field methodology will not be fully operational until June, 1977, yet ongoing investigation of lake eutrophication requires information concerning the winds at present. Thus a second objective was set. A quick and simple means of assessing the winds had to be developed for use until the primary method was operational. The remainder of this report details the selection, techniques, results and conclusions of this secondary wind analysis.

While one of the methods previously discussed could have been employed, it was decided to use wind data from Long Point, Ontario as an estimate of over-lake winds. Of the various land stations surrounding Lake Erie, Long Point offers the best approximation to the over-lake winds of the central basin (Burns and Ross, 1972). No pretense is made that Long Point is truly representative of the over-lake conditions. Its location, however, does offer minimal influence from surrounding land, the hourly data were readily available, and the data are sufficiently representative for the preliminary assessment required until the wind field methodology is available.

ANALYSIS

Data

This particular study uses hourly wind data obtained for the years 1973 through 1975. Since the lighthouse at Long Point operates only during the shipping season, wind data were only available for April through December. Wind data from other meteorological stations in close proximity to Lake Erie were also secured for use in later studies employing the wind field model. Meteorological observations taken aboard the *R/V Hydra* will be used in both the formulation and testing of the wind field model.

Technique

Two basic transformations of the raw data were performed. First, a "wind summary" was prepared. This wind summary was simply the listing, by month, of the hourly wind speeds and directions for all the data. Secondly, a "wind analysis" for various periods of time was conducted. This analysis yielded:

1. The resultant wind speed,
2. The direction of the resultant wind,
3. The persistance of the wind, and
4. The mean speed of the wind.

for the various periods selected. The resultant wind is the vectoral average of all wind directions and speeds during the selected periods. The individual observations are resolved into north and east components, and then averaged for the given period. The averaged components are then reconverted into a single vector. For a site with eight compass point directions, such as Long Point, the computation is rather simple (Panofsky and Brier 1965). If R_x is the component of the resultant wind in the east direction and R_y the component in the north direction, then:

$$R_x = \frac{\Sigma W - \Sigma E + .707(\Sigma SW + \Sigma NW) - .707(\Sigma SE + \Sigma NE)}{N}$$

$$R_y = \frac{\Sigma S - \Sigma N + .707(\Sigma SW + \Sigma SE) - .707(\Sigma NE + \Sigma NW)}{N}$$

In the numerator, W is the speed of each individual west wind, SE the magnitude of each south-east wind, and so forth. The denominator, N, is the number of observations during the time interval.

$$U_r = \sqrt{(R_x)^2 + (R_y)^2}$$

while the direction of the resultant wind (DIR_r) is

$$DIR_r = TAN\ (R_x/R_y)$$

The mean wind speed (U_m), regardless of direction, is

$$U_m = \frac{\Sigma N + \Sigma NE + \Sigma E + \Sigma SE + \Sigma S + \Sigma SW + \Sigma W + \Sigma NW}{N}$$

The speed of the resultant wind is smaller than the mean wind speed of the individual winds. A striking example of this would occur if the wind is equally likely to blow from all directions. In this case, the resultant wind would be zero.

The persistence (P) of the wind is defined by

$$P = \frac{U_r}{U_m}$$

Thus, if the wind blows from the same direction for the entire period, the persistence would equal 1.0, while in the case above of the equally distributed wind, the persistence would be 0.0. Persistence is an indicator of the regularity of the wind. The parameters U_r, DIR_r, and P are important in the study of waves, seiches, or currents, while U_m would be important in determining evaporation, cooling power or any variable determined by the strength of the wind and not its direction.

Wind histograms were also constructed for various periods based on the hourly wind data. A wind histogram is used to show the distribution of wind speeds and directions experienced at a given location over a specified period of time. Wind histograms were developed to illustrate the frequency of occurrence (by percent) of six wind speed classifications (0-10, 11-16, 17-21, 22-27, 28-33, and 34-40 knots) for the eight compass directions. The periods April through June and May through September were chosen because of their possible significance to the study of eutrophication in Lake Erie.

DISCUSSION

The results of this study are presented in two segments. The first segment is a general discussion of the winds observed during the entire study period. The second segment focuses around the analysis of the winds for April through June of each year. These three months represent a period of lake stratification. It was suggested that variations in the wind, which occurred during this period in 1975 (as compared to 1973 or 1974), may have influenced the formation of the thicker hypolimnion and high dissolved oxygen concentration.

General

The results of the wind analysis technique, when applied to monthly and yearly data, are presented in Table 22. General characteristics observed during all three years include:

TABLE 22. RESULTS OF THE WIND ANALYSIS FOR VARIOUS PERIODS AT LONG POINT, ONTARIO: 1973-1975

Period of Summation	1973				1974				1975			
	Resultant wind			Mean Velocity U_m (mph)	Resultant wind			Mean Velocity U_m (mph)	Resultant wind			Mean Velocity U_m (mph)
	Velocity U_r (mph)	Direction DIR_r (degrees)	Persistence P_r (%)		Velocity U_r (mph)	Direction DIR_r (degrees)	Persistence P_r (%)		Velocity U_r (mph)	Direction DIR_r (degrees)	Persistence P_r (%)	
April	1.77	313	9.5	18.68	9.66	219	49.9	19.34	6.05	308	34.9	17.37
May	4.71	219	28.6	16.46	4.87	229	30.0	16.23	3.82	231	29.7	12.85
June	8.04	210	56.7	14.18	6.14	198	42.5	14.45	3.79	215	27.4	13.84
July	4.14	227	31.1	13.32	6.06	233	47.6	12.71	7.11	236	58.7	12.12
August	4.55	235	37.7	12.08	4.32	210	35.3	12.29	2.59	220	19.3	13.42
September	1.89	274	12.7	14.83	5.31	243	33.0	16.09	4.31	258	27.6	15.61
October	1.62	244	10.3	15.69	7.02	261	41.2	17.06	4.92	252	27.3	18.06
November	10.42	255	49.1	21.21	7.04	262	36.2	19.43	11.68	239	59.8	19.54
December	3.64	232	18.7	19.47	5.45	261	25.7	21.20	4.82	242	22.6	21.36
April through June	4.27	221	26.1	16.39	6.72	215	40.3	16.66	3.33	259	22.7	14.66
April through December	4.19	235	26.6	15.77	5.76	235	35.3	16.31	4.96	246	31.5	15.73

1. The annual resultant wind is from the west-southwest at approximately 5.0 mph.

2. During the year, the resultant wind velocity (U_r) is greatest in the late fall with a secondary maximum in the spring. The minimum resultant wind velocity consistently occurs in late summer. This same trend is also apparent in the mean wind velocity (U_m).

The first characteristic reflects the location of lake within the westerly wind belt of the general circulation. The dominance of southwest winds is further emphasized in Table 23, which lists the percent frequency of wind direction for the eight compass directions for each year. The second characteristic is graphically presented in Figure 53. The original monthly resultant wind velocities were smoothed by means of a three month overlapping average to facilitate analysis. The observed trend can be explained by two plausible factors, (1) seasonal changes within the general circulation and (2) stability. During the summer the mean hemispheric pressure gradient is reduced, and the westerly wind belt is diplaced northward. As a consequence of these seasonal changes, Lake Erie experiences weaker, less persistent winds. The lake is cooler in the summer than the air above it. This condition inhibits mixing and thus reduces the surface winds. Both proposed factors should be fully investigated.

April through June

The thermal stratification of the lake, which is affected by currents, seiche activity and waves is dependent to some extent on the surface wind speed, the duration of the wind from a given direction (persistence), fetch (determined by wind direction) and atmospheric stability.

Atmospheric stability is evaluated by computing the air-water temperature difference (ΔT) between the average daily water temperature at Marblehead, Ohio and the average daily temperature at Sandusky, Ohio. These results are not representative of the stability conditions for the entire lake, instead the results are meant merely to serve as a first approximation to assessing stability. The average values of ΔT for this period were 2.2°C, 2.1°C, and 1.6°C for 1973, 1974 and 1975 respectively. While ΔT is positive, indicating a stable layer of air, ΔT is not large enough to influence the winds significantly (Jacobs, 1965; Strong and Bellaire, 1965).

TABLE 23. PERCENT FREQUENCY OF THE 8-POINT WIND DIRECTIONS DERIVED FROM HOURLY WIND DATA FOR LONG POINT, ONTARIO, APRIL-DECEMBER, 1973-1975

Year	Direction and Percent Frequency							
	N	NE	E	SE	S	SW	W	NW
1973	6.6	15.1	7.3	4.9	12.9	31.4	11.3	10.7
1974	8.7	11.9	5.8	5.4	12.0	35.3	11.3	9.4
1975	7.7	9.9	7.3	5.5	12.0	28.5	16.1	12.9

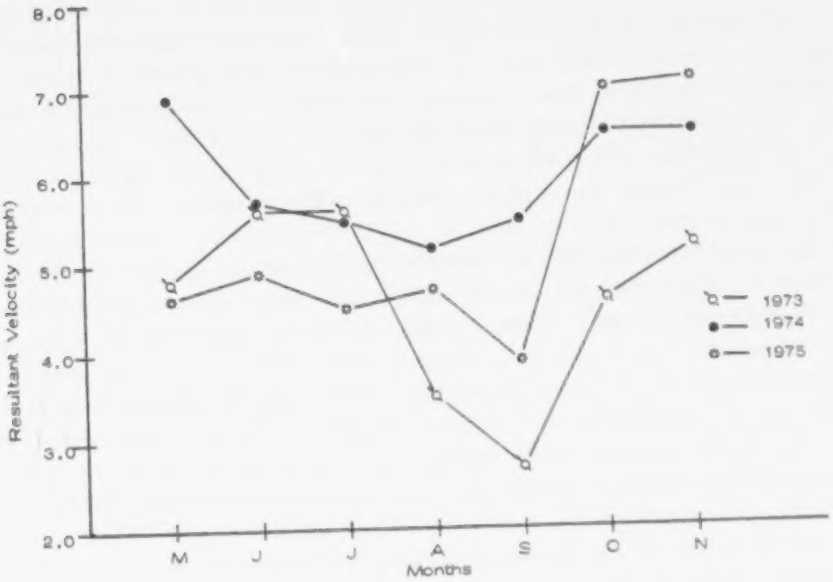

Figure 53. Monthly resultant wind velocities for Long Point, Ontario.

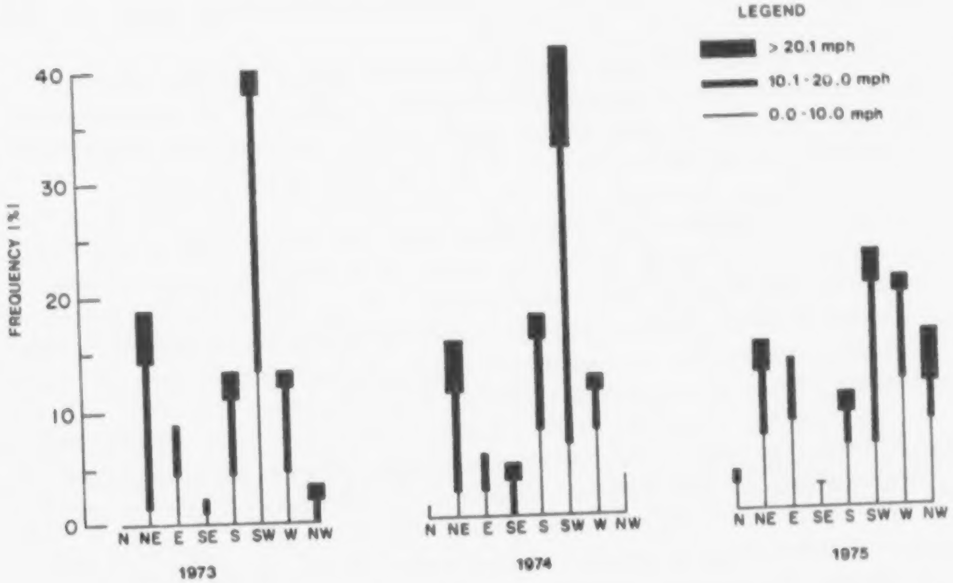

Figure 54. Histogram of resultant winds at Long Point, Ontario, April-June 1973-1975.

Inspection of the wind analysis results (Table 22) during this period of time reveal slight but important differences between 1975 and 1973 or 1974. In 1975, both the resultant wind velocity and the mean wind velocity were lower than the previous two years. Also, in 1973 and 1974 the resultant wind directions were 221° and 215° respectively, while in 1975 the resultant wind direction was 259°. A wind histogram, computed from the daily resultant winds of this period, is presented in Figure 54, and helps to explain these differences. The dominance of the southwest winds is obvious in 1973 and 1974. During 1975, however, although prevailing southwest winds continued to be present, a much more uniform distribution occurred. In fact, southwest winds, which produce the greatest over-lake fetch for this location, occurred almost twice as often in 1973 (39.9 percent) and 1974 (41.7 percent) as compared to 1975 (22.2 percent). Also, the winds, regardless of direction, had lower magnitudes in 1975 than either 1973 or 1974. Only 53 percent of the winds during this period in 1975 were greater than 10 miles per hour, while for the same period in both 1973 and 1974, 70 percent of the winds were in excess of 10 miles per hour. The winds from April through June 1975 were weaker and more evenly distributed than for the same period during either 1973 or 1974 (Figure 54).

CONCLUSIONS

The following conclusions can be made from this study:

1. Although the predominant winds at Long Point, Ontario are from the southwest (average speed 11-16 knots), the distribution of the winds often show marked variation from month to month or even year to year.

2. The distribution of the winds for April through June 1975 was significantly different from the distributions of the same period in 1973 and 1974. Such differences in the wind are an important element in the assessment of physical, chemical, or biological processes occurring in the lake.

3. The Long Point, Ontario wind data offers an unrefined estimate of the central basin winds which is sufficient for examining the gross relationships between wind and other parameters. For more detailed studies involving spatial variation, the wind field method will be necessary.

4. There is a need for more reliable and more frequent over-lake measurements, possibly from permanent

buoys. Also, other meteorological elements such as rainfall, solar radiation, evaporation, etc. should be monitored at both coastal and over-lake sites and analyzed for possible influences on lake eutrophication.

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SECTION 6

PHOSPHORUS BUDGET OF THE CENTRAL AND WESTERN BASINS OF LAKE ERIE: 1973-1975

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INTRODUCTION

Nutrient budget studies provide a basis for the quantitative assessment of the net transfer of materials between conceptualized compartments of a lake. Budgets greatly aid in the investigation of prevailing transport mechanisms and the fate of transported materials. This part of the report will present the phosphorus budget as determined by field measurements and estimated loadings for the 1973, 1974 and 1975 field seasons (April through December). The number and locations of the western and central basin sampling stations, procedures for sample preparation, and methods of analysis have been detailed in the Overview section.

PROCEDURES

A scheme devised by Noel Burns (CCIW) dividing Lake Erie into grids of estimated area (Overview, Figure 3) was used in estimating the quantities of phosphorus (P) measured in the western and central basins. The western basin was divided into seven grid areas (grids 44 through 50) and the central basin into 25 grid areas (19 through 43). The epilimnion, mesolimnion and hypolimnion volumes for each grid and survey were calculated by the procedure outlined in the Overview section.

The concentrations measured at stations within each grid were used to calculate the quantity of P for that grid. During unstratified periods the quantity of P in each grid was obtained by multiplying the average concentration measured within the grid by the total grid volume. Concentrations of P were found to be nearly uniform throughout the water column during unstratified periods, thus the average of the concentration measurements yielded a reliable estimate. During stratified periods the quantity of P was calculated for each of the three limnions by multiplying the limnion volume by its average concentration. The quantity of epilimnion P for each grid was estimated from the average concentration taken at one meter below the surface. The measurements taken one meter above the mesolimnion were not included in determining the epilimnion quantity of P, since a high concentration gradient may exist through the mesolimnion and could lead to overestimation of epilimnion P if the two values were averaged. The quantity of P in the mesolimnion was estimated by using the average of the concentrations measured one meter above and one meter below the mesolimnion. The hypolimnion quantities of P for each grid were estimated by averaging the concentrations measured one meter below the mesolimnion and one meter above the bottom. During anoxic conditions, when a sharp increase in the P concentration gradient existed below the bottom sampling horizon the quantity of P in the hypolimnion was considered to be underestimated. The accuracy of all P quantity estimates largely depends on the accuracy of the volume estimates of the three limnions.

The total quantities for the entire central basin and western basin were calculated by summing the estimated total quantity of P for each grid within the basin. For budget calculations during stratified periods, the epilimnion was considered to consist of both the epilimnion and mesolimnion. Due to intermixing between the two limnions and volume fluctuations occuring in the mesolimnion the two limnions were combined, as was done by Burns (1976). The total central basin or western basin epilimnion quantity of P was then determined by summing the combined values for all grids within the basin. Similarly the total basin hypolimnion quantity was determined by summing the hypolimnion P quantity of all grids within the basin.

The volume-weighted concentrations for the western and central basins were calculated by summing the estimated total quantities of P for each grid and dividing by the total basin volume. The volume-weighted concentrations for each limnion were similarly calculated, using the volume and quantities appropriate for the respective limnion.

Table 24 shows the calculated volume-weighted concentrations and quantities of total phosphorus (TP) used for the 1973 through 1975 central basin P budget calculations. Similar calculations were made for the western basin total phosphorus budget.

TABLE 24. CONCENTRATION AND QUANTITIES OF PHOSPHORUS FORMS IN LAKE ERIE CENTRAL BASIN

Year	Cruise No.	Conditions	-Limnion	Volume Km^3	Total Phosphorus		Soluble Reactive Phosphorus		Particulate Phosphorus		Soluble Organic Phosphorus**	
					Metric Tons	conc. µgm/L	Metric Tons	conc. µgm/L	Metric Tons	conc. µgm/L	Metric Tons	conc. µgm/L
1973	2	Stratified	Epi	228.63	3584.01	14.20						
			Meso	22.22								
			Hypo	61.31	940.65	15.34						
	5	Stratified	Epi	238.20	3553.08	13.51						
			Meso	24.86								
			Hypo	47.07	1004.13	21.33						
	7	Unstratified	-	306.09	7839.90	25.00						
1974	2	Unstratifed	-	311.94	5247.19	10.82						
	4	Stratified	Epi	195.82	2635.52	13.48						
			Meso	22.74	431.60	18.98						
			Hypo	93.67	1962.42	20.95						
	5	Stratified	Epi	249.10	3362.87	13.50	269.03	1.10				
			Meso	12.52	203.89	16.29	27.75	2.20				
			Hypo	50.12	961.30	19.18	140.24	2.79				
	7	Stratified	Epi	235.35	3058.23	12.99	247.54	1.05				
			Meso	23.83	282.38	11.85	41.71	1.75				
			Hypo	50.63	864.15	17.07	170.74	3.37				
	8	Stratified	Epi	243.01	4534.88	18.66	395.17	1.63				
			Meso	17.45	296.37	16.98	109.12	6.25				
			Hypo	48.38	1378.20	28.49	743.05	15.36				
	10	Unstratified	-	303.97	6046.21	19.89	629.02	2.07				
1975	1	Unstratified	-	308.69	7100.86	23.00	567.99	1.90	5864.62	19.00	648.25	(2.55)
	2	Suratified	Epi	174.03	2421.42	13.91	457.19	2.63	1590.77	9.19	365.46	(2.16)
			Meso	30.76	469.27	15.26	70.94	2.31	333.73	10.85	64.60	(2.11)
			Hypo	104.70	1638.34	15.65	241.96	2.31	1176.51	11.24	219.87	(1.79)
	3	Stratified	Epi	182.64	2357.01	12.91	288.87	1.58	1684.00	9.22	383.54	(2.89)
			Meso	35.56	637.71	17.94	66.26	1.86	496.77	13.97	74.68	(3.83)
			Hypo	90.49	1919.77	21.22	208.95	2.31	1520.79	16.81	190.03	(3.40)
	4	Stratified	Epi	227.39	3488.53	15.34	632.07	2.78	2378.94	10.46	477.52	(1.40)
			Meso	15.23	215.86	14.17	40.10	2.63	143.78	9.44	31.98	(0.79)
			Hypo	66.07	1183.63	17.91	272.98	4.13	771.90	11.68	138.75	(0.00)
	5	Unstratified	-	307.06	6134.24	19.98	812.36	2.65	4677.05	15.23	644.83	(2.56)
	6	Unstratified	-	303.96	3623.04	31.66	2480.56	8.16	6504.16	21.40	638.32	(1.27)
	1→6	Average volume time weighted		307.82	6013.11	19.53	996.67	3.24	4370.03	14.20	646.43	2.10
	1→6	Percent of total phosphorus			100.00%		16.57%		72.68%		10.75%	

* Volume weighted

** The concentration of soluble organic phosphorus was determined by difference (the values in parenthesis) and is, therefore, least accurate. For calculation of tons of soluble organic phosphorus in this table the value of 2.10 µgm/L was assumed constant throughout the season (cruises).

In order to obtain a better understanding of the phosphorus budget during 1975, total filtered phosphorus (TFP) and particulate phosphorus (PP) were measured in addition to TP and soluble reactive phosphorus (SRP). Fourteen central and western basin stations were selected for these additional measurements of P forms. The concentration and quantities of PP and soluble organic phosphorus (SOP) were estimated for all the grids by interpolation and extrapolation from the measured concentrations at the 14 selected stations. Even though the estimates made reduced the reliability of the PP and SOP data, the information was valuable in clarifying some aspects of the transformations of P forms in the water.

The preliminary estimates of annual TP loadings (Table 25) and monthly and daily average loading of TP and SRP (Table 26) were obtained from the Army Corps of Engineers, Buffalo District (1977). The daily estimates were used to determine the quantity of P entering the western and central basins between consecutive cruises. The phosphorus loading contributed from precipitation (approximately 900 metric tons yearly for the entire lake) and the apatite phosphorus contributed from shoreline erosion, which is not considered to interact in lake water columns (Burns, 1976), were not accounted for and will not be considered in the P budget.

Water flow rates, P loadings and concentrations of P at the inlets and outlets of the central basin were required to estimate the quantity transferred and the quantity retained for both basins. Measured flow rates for the separate basins were not available; thus, the flow rates (1973-1975) were estimated using a fraction of the total flow into the lake (Table 27). The estimates were based on 1970 data presented by Burns (1976).

The average concentration of P at transects 1 and 6 (Figure 55) was used to estimate the quantity of P input into the central basin from the western basin and output from the central basin to the eastern basin. It was assumed the western basin flow into the central basin was confined to the epilimnion and mesolimnion during the stratified period. Since at transect 1, stratified conditions rarely existed, concentrations measured at all depths were averaged to estimate the quantity of P input from the western basin. A similar procedure was used to estimate the quantity of P leaving the central basin. Since transect 6 is stratified during the summer months, the average epilimnion and mesolimnion volume-weighted concentrations were used to quantify the amount of P transported out of the basin. During unstratified periods, average values for the entire water column were used for the discharge estimate.

TABLE 25. TOTAL PHOSPHORUS INPUT IN LAKE ERIE METRIC TONS[1]

Year / Basin / [2]Sources	1973		1974		1975	
	Western	Central	Western	Central	Western	Central
Detroit River	11822		11264		10111	
Point	1332	2175	1034	1969	1074	1886
Diffuse	4351	1816	4341	2261	3748	1956
Total	17505	3991	16639	4230	14933	3842
Western basin and central basin	21495		20869		18775	
TOTAL LAKE	23188		22912		20434	

[1] Data Source: U.S. Army Corps of Engineers, Buffalo District.

[2] Input by precipitation and northern shore erosion (apatite phosphorus) are not considered.

TABLE 26. LAKE ERIE WESTERN AND CENTRAL BASIN AVERAGE DAILY TOTAL AND SOLUBLE REACTIVE PHOSPHORUS LOADS METRIC TONS - 1975

Month	Source / Basin	Total Phosphorus (m-tons/day) Detroit River	Non-Point	Point	Total	Soluble Reactive Phosphorus (m-tons/day) Detroit River	Non-Point	Point	Total
Jan	Western	27.450	16.187	2.957	46.594	12.590	3.755	1.479	17.824
	Central		13.029	5.484	18.513		2.085	2.551	4.635
	W.B.+C.B.	27.450	29.216	8.441	65.107	12.590	5.840	4.030	22.459
Feb	Western	27.210	27.198	2.957	57.365	12.480	6.503	1.479	20.462
	Central		19.567	5.484	25.052		2.668	2.528	5.196
	W.B.+C.B.	27.210	46.765	8.441	82.417	12.480	9.171	4.007	25.658
Mar	Western	26.250	8.921	2.957	38.128	12.040	2.871	1.479	16.390
	Central		11.444	5.484	16.928		2.095	2.650	4.744
	W.B.+C.B.	26.250	20.365	8.441	55.050	12.040	4.966	4.129	21.134
Apr	Western	27.690	7.046	2.957	37.693	12.700	2.439	1.479	16.618
	Central		1.654	5.186	6.840		0.478	2.022	2.499
	W.B.+C.B.	27.690	8.700	8.143	44.533	12.700	2.917	3.501	19.117
May	Western	27.690	13.320	2.957	43.967	12.700	2.532	1.479	16.711
	Central		2.106	5.484	7.390		0.535	2.203	2.737
	W.B.+C.B.	27.690	15.426	8.441	51.557	12.700	3.067	3.682	19.448
June	Western	28.290	12.779	2.957	44.026	12.970	2.383	1.479	16.832
	Central		3.953	5.423	9.376		0.506	2.407	2.913
	W.B.+C.B.	28.290	16.732	8.380	53.402	12.970	2.889	3.886	19.745
July	Western	28.530	3.867	2.902	35.299	13.080	0.303	1.452	14.834
	Central		0.161	4.336	4.496		0.076	1.752	1.828
	W.B.+C.B	28.530	4.028	7.238	39.795	13.080	0.379	3.204	19.682
Aug	Western	28.530	3.341	2.906	34.776	13.080	0.550	1.479	15.109
	Central		1.421	4.798	6.219		0.357	1.935	2.292
	W.B.+C.B.	28.530	4.762	7.704	40.995	13.080	0.907	3.414	17.401
Sept	Western	28.770	5.559	2.957	37.286	13.190	1.332	1.479	16.001
	Central		4.381	5.403	9.785		0.836	2.400	3.236
	W.B.+C.B.	28.770	9.940	8.360	47.071	13.190	2.168	3.879	19.237
Oct	Western	27.570	3.547	2.942	34.059	12.640	0.493	1.368	14.501
	Central		0.723	4.824	5.547		0.227	1.968	2.196
	W.B.+C.B.	27.570	4.270	7.766	39.606	12.640	0.720	3.336	16.697
Nov	Western	27.330	0.927	2.916	31.173	12.530	0.465	1.384	14.378
	Central		0.711	4.634	5.345		0.289	1.846	2.135
	W.B.+C.B.	27.330	1.638	7.550	36.518	12.530	0.754	3.230	16.513
Dec	Western	27.090	21.704	2.957	51.751	12.420	3.197	1.479	17.096
	Central		6.193	5.484	11.678		1.033	2.302	3.335
	W.B.+C.B.	27.090	27.897	8.441	63.429	12.420	4.230	3.781	20.431

* Corps of Engineers, Buffalo District Preliminary Estimates.

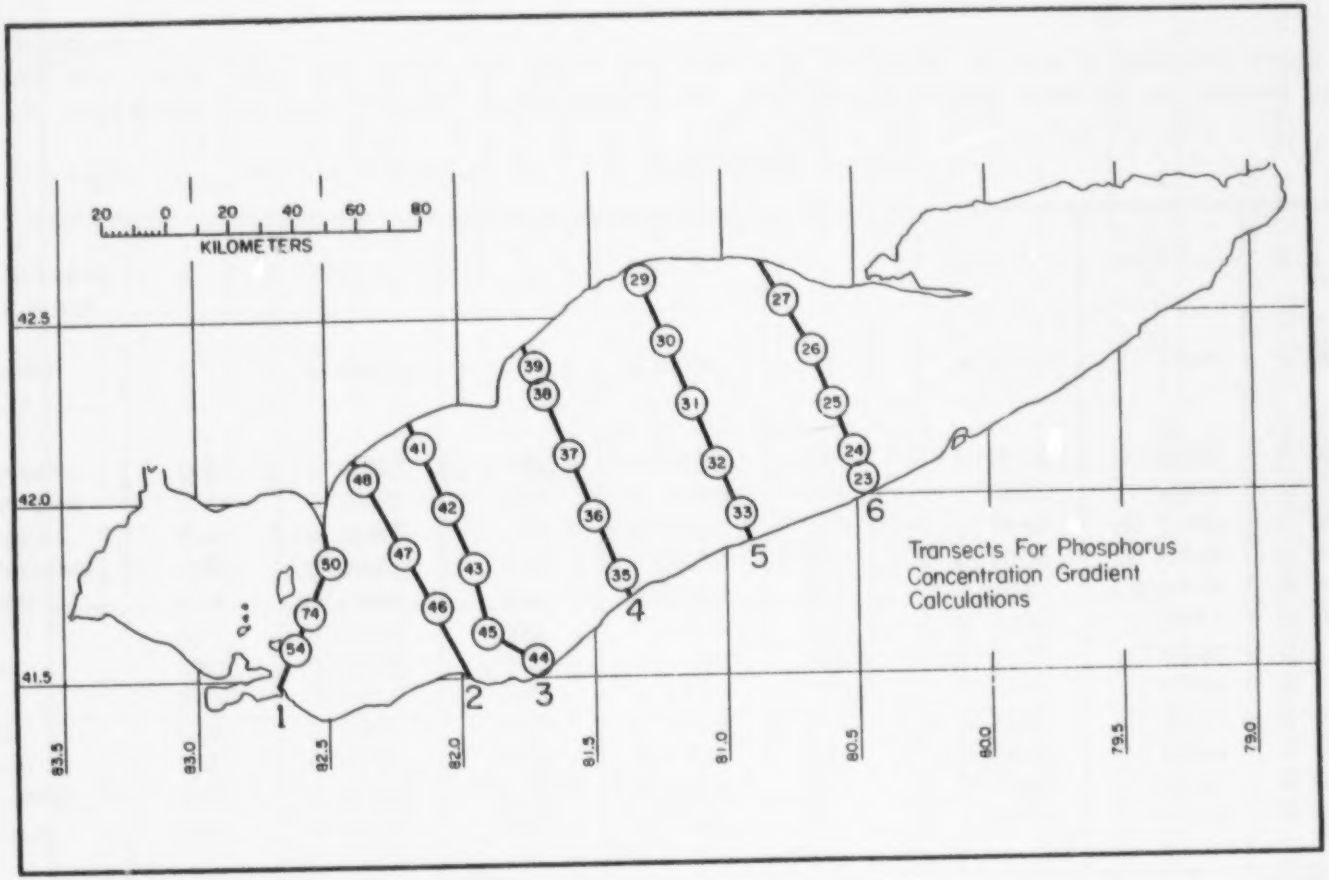
TABLE 27. FLOW RATES OF WATER INTO LAKE ERIE[1]

Year / Month	1973		1974		1975		1975[2]	
	$\text{CFT}/\text{SEC} \times 10^{-3}$	KM^3/DAY	$\text{CFT}/\text{SEC} \times 10^{-3}$	KM^3/DAY	$\text{CFT}/\text{SEC} \times 10^{-3}$	KM^3/DAY	Into W.B. and out to C.B.	KM^3/DAY Out of C.B.
January	254	0.6214	280	0.6850	271	0.6630	0.6376	0.6529
February	215	0.5260	252	0.6165	261	0.6386	0.6141	0.6288
March	360	0.8808	324	0.7927	271	0.6630	0.6376	0.6529
April	269	0.6581	274	0.6704	255	0.6239	0.6000	0.6144
May	267	0.6532	294	0.7193	257	0.6288	0.6047	0.6192
June	290	0.7095	253	0.6190	266	0.6508	0.6259	0.6408
July	234	0.5725	231	0.5652	210	0.5138	0.4941	0.5059
August	218	0.5334	206	0.5040	247	0.6043	0.5812	0.5951
September	191	0.4673	205	0.5015	229	0.5603	0.5388	0.5517
October	204	0.4991	164	0.4012	194	0.4746	0.4564	0.4673
November	220	0.5383	294	0.7193	216	0.5285	0.5083	0.5204
December	257	0.6288	197	0.4820	254	0.6214	0.5976	0.6119
Yearly Average		0.6082		0.6060		0.5973	0.5744	0.5882
Total Flow per year(Km^3)		222.0		221.2		218.0	209.7	214.7

[1] Flow rates in CFT/SEC were estimated by U.S. Geological Survey.

[2] The flow rates into the western basin and out to the central basin, and out of central basin were estimated from the total flow rates into the lake by using factors 0.962 and 0.985 respectively.

Note: The gain of water from precipitation and losses due to evaporation are not accounted for.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Transects For Phosphorus
Concentration Gradient
Calculations

Figure 55. Transects for phosphorus concentration gradient calculations.

To estimate the P input into the central basin from the western basin between consecutive cruises, the product of the average P concentration, the flow rate into the central basin, and the time elapsed between the two cruises were utilized. A similar procedure was used to estimate the between cruise quantity of P moving from the central basin and into the eastern basin.

The estimated quantities of P entering and leaving the central basin were calculated, neglecting the flow vector and limiting the P distribution in and out of the basin to a vertical epilimnion transect. Consequently these estimates of input and output were questioned relative to the actual expected quantities of P transported within the lake. The estimated input to the central basin at transect 1 should represent approximately ± 5 percent of the actual quantities since the flow rate is relatively high and uniform throughout the transect with insignificant backflow expected. The conditions at transect 6 are more complex. The flow velocity and the concentration of P (due to point sources and the flow from the western basin) is highest along the southern shoreline, while the reverse is true along the northern shore. Eastern basin water of lower P concentration may entrain into the central basin, which further complicates the flow at transect 6. From unpublished data and measured concentrations of P taken in the vicinity of transect 6, an error of ± 10 percent was estimated. Consequently the calculated quantity of TP retained in the central basin has an estimated deviation of ± 3 to ± 4 percent. Good agreement was found when the P retention estimates for the western and central basin were compared with those of Burns (1976) who utilized more extensive procedures to estimate retentions. Thus, the simplified procedure was considered to be satisfactory.

The mean epilimnion P concentrations for transects 1 and 6 presented in Table 28 are used for calculating TP inputs and outputs to and from the central basin for cruises 1 through 6 during 1975. In addition, the estimated TP concentrations for transects 2 through 5, and the estimated mean volume-time weighted TP concentrations for cruise 1 to 6 for each transect are presented in Table 28. The estimated epilimnion TP concentrations for each cruise at each transect are plotted in Figure 56. The concentration for each cruise was considered to be 100 percent at transect 1 and the concentrations at the successive transects (2 through 6) were expressed as a percent of the concentration at transect 1. The low concentration at transect 2 is the result of the estimation procedure and may not represent actual conditions. High TP concentrations and high flow rates occurred along the south shore at transect 2 and an entrainment of low TP water occurred in the northern central part of the transect. Consequently

TABLE 28. AVERAGE PHOSPHORUS CONCENTRATION IN LAKE ERIE CENTRAL BASIN AT TRANSECTS 1 THROUGH 6 IN PPB

Transect No. / Cruise No.	1	2	3	4	5	6
1	48.21	20.52	28.75	24.27	18.23	19.84
2	29.64	9.93	13.01	14.25	11.03	13.52
3	24.92	12.29	11.40	14.50	13.18	12.37
4	29.27	15.61	22.77	12.90	10.67	10.51
5	32.40	19.61	19.66	19.37	18.56	17.20
6	34.93	27.60	29.28	39.50	29.93	27.34
1 → 6	32.15	17.06	19.87	19.88	16.45	16.26

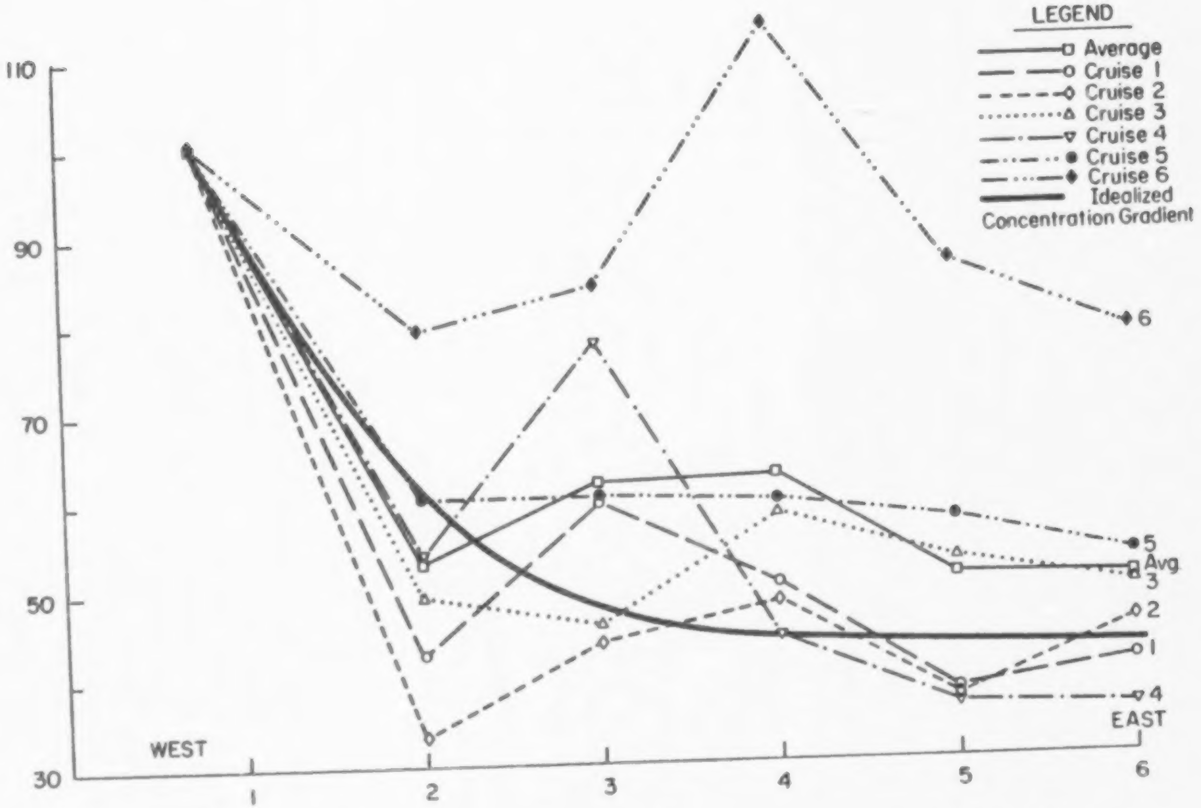


Figure 56. Epilemnetic phosphorus concentration gradient for Lake Erie central basin.

it was felt that the calculation procedure led to a significant underestimation of the average phosphorus concentration at transect 2. A similar but less significant effect influenced transects 3, 4 and 5 during cruise 1, 2, 3 and 5. During cruise 4 (late August) a peak concentration occurred at transect 3 which was attributed to anoxic regeneration in and around grids 38 and 41 prior to cruise 4. The high concentration of TP at transect 4 during cruise 6 appeared to be the result of resuspended PP and SRP from the sediments and interstitial water during the fall storms. The idealized TP concentration gradient from transect 1 through 6 is represented by the solid curve (Figure 56). The sharp decrease between transects 1 and 3 is largely attributed to settling of PP which enters the central basin from the western basin.

Burns' (1976) Exchange Model procedure was followed for estimating the epilimnion budget. The quantity of phosphorus transported to the epilimnion by the hypolimnion volume incorporation was obtained by the product:

$$\Delta V_h \quad \times \quad Cpa$$

where $\Delta V_h = V_h(n-1) - V_h(n)$ and ΔV_h is the hypolimnion volume decrease between cruise n-1 and n, and $V_h(n-1)$, $V_{h(n)}$ are the corresponding hypolimnion volumes; Cpa is the average area-weighted upper hypolimnion phosphorus concentration of cruise n-1 and n.

The quantity of phosphorus transported to the epilimnion out of the hypolimnion by the exchange process with no associated hypolimnion volume change (Pe) was calculated by the equation:

$$Pe = \Delta Pg \left(\frac{He}{\Delta Tg} \right)$$

where ΔPg is the mean area-weighted phosphorus concentration gradient through the mesolimnion, He is the heat transferred into the hypolimnion by the exchange process with no associated hypolimnion volume change and ΔTg is the mean area-weighted mesolimnion temperature gradient. The area weighted phosphorus concentrations were calculated using the same calculation procedure used to determine the volume weighted concentrations, but instead of volumes, the areas of the particular grids were used. The He and ΔTg were calculated by J. Zapotosky for estimates of heat transfer. Generally, the concentration of nutrients in the hypolimnion is greater than the epilimnion concentration and the Exchange Model can be used to estimate the transport of nutrients to the mesolimnion and/or epilimnion.

PHOSPHORUS BUDGET

As stated earlier, the phosphorus budget presented in this report does not include the contribution of P from precipitation or apatite phosphorus contributed from shoreline erosion. The budget is a net budget; thus, the quantity transferred into and out of any lake compartment in equal amounts is not taken into account.

The equation used to estimate the loss or gain of Phosphorus in the lake water:

$$\text{In} - \text{Out} = \text{Accumulation}$$

and

$$\text{In} - \text{Out} = \text{Accumulation} = \text{Imbalance}$$

1973 TOTAL PHOSPHORUS BUDGET

During the 1973 cruise season (Table 29) three "nutrient cruises" were conducted. Total phosphorus data used to estimate the 1973 western basin phosphorus budget for the 90-day cruise period (cruises 2-7) are presented in Table 30. Diffuse sources accounted for only 1.2 percent of the total external phosphorus loading to the western basin during this period. This low contribution from diffuse sources was typical for the summer and fall months when tributary flows were low. From cruise 2 to 5, 63.8 percent of the total P input to the western basin remained in the basin due to settling, while 34.5 percent was transported into the central basin. The remaining 1.7 percent stayed in the western basin water mass. Between cruises 5 and 7, 30.1 percent of the loading to the western basin settled, 45.6 percent was transported into the central basin and 24.3 percent remained in the water mass. Comparison of the quantities of total phosphorus settled to the quantities of phosphorus retained in the water mass during cruises 2-5 and cruises 5-7 reveals a striking difference. From cruise 2 to 5, the percent of TP settled was large, while from cruise 5 to 7, a larger percentage was retained in the water mass. The large percentage settled from cruise 2 to 5 resulted from the settling of resuspended materials. Cruise 2 followed a period of high winds in the western basin causing the resuspension of large quantities of particulate matter. This was evidenced by the presence of the largest quantities of pheopigment encountered during the entire study period. The 2-5 cruise interval indicated a sharp increase in biological activity when the chlorophyll a concentration increased 3.5 µg/l. During the time interval of cruises 5-7, there was a large increase of P in the water and less net settling, and no change in corrected chlorophyll a was apparent. At the time

TABLE 29. "CLEAR" NUTRIENT CRUISE TIMETABLE

Year	Date	Cruise No.	Days between cruises	Period/ Days
1973	7/17–7/24	2		
	8/29–9/4	5	42	
	10/14–10/24	7	48	90
1974	4/25–5/4	2		
	6/1–6/10	4	36	
	6/28–7/7	5	28	
	8/12–8/19	7	44	
	8/26–9/7	8	16	
	10/21–11/1	10	56	180
1975	3/27–4/25	1		
	6/9–6/19	2	51	
	7/13–7/21	3	33	
	8/30–9/5	4	49	
	9/27–10/6	5	28	
	12/2–12/14	6	65	226

TABLE 30. LAKE ERIE WESTERN BASIN
TOTAL PHOSPHORUS BUDGET (METRIC TONS)
JULY 17–OCTOBER 24, 1973

Cruise Interval		In to W.B.	Out to C.B.	Changes in Water Mass	Net Settling	Net Regeneration	In the Water Mass	
Cruise No.	Days						Cruise No.	Metric Tons
2→5	42	+1679	- 579	+28	-1072	-	2	648
5→7	48	+1707	- 778	+415	- 514	-	5	677
2→7	90	+3386	-1357	+443	-1586	-	7	1091
2→7	From total input retained in Western Basin		59.92%					

cruise 7 was made (mid October), severe storms and high wind conditions existed. These conditions resulted in the resuspension of sedimented particulate matter, thus contributing appreciably to the high P in the water and low settling rates.

Another source of P to the water mass could have been supplied during later August-early September (cruise 5) when anoxic conditions prevailed throughout much of the central basin and possibly the western basin. The concentration of TP could have increased due to the regeneration of SRP from the sediments. Generally, stratification is not observed in the western basin; however, an ephemeral stratified condition may develop. A thin hypolimnion in the western basin will become anoxic in a short period due to the high organic content of the sediment and will result in high oxygen depletion rates. An alternate mechanism for the development of anoxic conditions in the western basin at the sediment-water interface, the oxygen transfer rate to the interface may become lower than the depletion rate, thus causing the formation of an anoxic layer above the sediments. Either mechanism may occur only at zero or slow wind speeds, but regardless of the mechanism, entry of P into the water mass from the sediment will result. Occasionally, bottom water samples with unusually high phosphorus concentrations were taken in the western basin, which substantiate a mechanism of phosphorus regeneration in the basin. The western basin budget for the entire 1973 cruise period shows that 59.9 percent of the total phosphorus loading into the western basin was retained in the sediments, and consequently there was a substantial quantity of phosphorus available to the water mass through anoxic and/or physical regeneration.

For the entire 1973 cruise season (cruises 2-7), 46.8 percent of the external P loading entering the western basin settled in the western basin and 13.1 percent remained in the water mass. The central basin received 40 percent of the external loading to the western basin, which indicates that the western basin served as a sink for nearly 47 percent of the total P loading.

The 1973 central basin total phosphorus budget (Table 31) showed a net settling of 546 metric tons from cruises 2-5, while from cruises 5-7, a net regeneration of 2,571 metric tons took place. This high regeneration is attributed to the extensive anoxic hypolimnion (11,270 km^2) and physical regeneration due to sediment resuspension during cruise 7 storm conditions. The internal loading from cruise 5 and 7 due to regeneration exceeded the external loading during this period by 1,545 metric tons.

TABLE 31. LAKE ERIE CENTRAL BASIN
TOTAL PHOSPHORUS BUDGET (METRIC TONS)
JULY 17-OCTOBER 24, 1973

Cruise Interval		In From			Out to E.B.	Changes in Water Mass	Net Settling	Net Regen-eration	In the Water Mass	
Cruise No.	Days	W.B.	Point Sources	Diffuse Sources					Cruise No.	Metric Tons
									2	4505
2 → 5	42	+578	+226	+24	-229	+53	-546		5	4557
5 → 7	48	+778	+241	+ 7	-314	+3283		+2571	7	7840
2 → 7	90	+1356	+467	+31	-543	+3336		+2025		
2 → 7		From Total input retained in central basin			70.71%					

Thus during anoxia, the central basin became a source of phosphorus instead of a sink. The central basin budget also showed 70.7 percent of the 1973 external phosphorus loading to the central basin was retained within the basin. The combined central and western basin budget for 1973 (cruises 2-7, Table 32) showed a net internal loading (regeneration) of 438 metric tons with 86 percent of the total external loading being retained in the western and central basins.

1974 BUDGET

The 1974 western basin total phosphorus budget is shown in Table 33. The peak external total phosphorus loading to the western basin occurred between cruises 2-4. The main total phosphorus loading enters the western basin from the Maumee, Detroit and other rivers during spring run-off. At this time 1,708 metric tons or 47.4 metric tons/day of P was released into the western basin, of which 1,437 metric tons, or 84.1 percent, of the external loading settled in the western basin. In late spring and summer external loading decreased and reached a minimum of 34.1 metric tons/day between cruises 7 and 8. A decrease in settling was observed during the summer with the cruise 7 to 8 period having a net settling of only 55 metric tons. This period coincided with the time of maximum anoxia and regeneration in the central basin, thus the low net settling may have resulted from regeneration of P in the western basin. This phenomenon was previously discussed in conjunction with the 1973 western basin total phosphorus budget. During the fall cruises 8 through 10, net settling again increased with 62.1 percent of the external loading being retained within the basin. As in 1973, the western basin acted as a P sink with 59.1 percent of the total external phosphorus loading retained in the western basin during the 1974 season (cruises 2-10, Table 33).

The 1974 central basin total phosphorus budget (Table 34) showed a considerable decrease of external loading from the spring through the summer months. The external loading decreased from 27.4 metric tons/day between cruises 2 and 4 to 22.1 metric tons/day between cruises 7 and 8 with a particularly large decrease of diffuse source loading apparent. Net settling showed a slight increase from spring through the early summer (cruise 2 to 7). From cruise 7 to 8 there was an increase of 2,005 metric tons of P in the water column due to an estimated regeneration of 1,723 metric tons of P. This increase of P coincided with the maximum extent of anoxia during 1974, with an estimated anoxic hypolimnion area of 10,250 km^2. The budget showed 1,820 metric tons of total phosphorus settled and 67.4 percent of the total external phosphorus loading was retained in the

TABLE 32. LAKE ERIE WESTERN PLUS CENTRAL BASIN TOTAL PHOSPHORUS BUDGET (METRIC TONS) JULY 17-OCTOBER 24, 1973

Cruise Interval		In	Out to E.B.	Changes in Water Mass	Net Settling	Net Regeneration	In the Water Mass	
Cruise No.	Days						Cruise No.	Metric Tons
							2	5153
2 → 5	42	1929	-229	+ 81	-1619	-	5	5234
5 → 7	48	1955	-314	+3698		+2057	7	8931
2 → 7	90	3884	-543	+3779		+ 438		
2 → 7	From total input retained in western and central basin	86.02%						

TABLE 33. LAKE ERIE WESTERN BASIN
TOTAL PHOSPHORUS BUDGET (METRIC TONS)
APRIL 25-NOVEMBER 1, 1974

Cruise Interval								In the Water Mass	
Cruise No.	Days	In to W.B.	Out to C.B.	Change In Water Mass	Net Settling	Net Regeneration	Retained %	Cruise No.	Metric Tons
								2	1056
2→4	36	1708	- 581	-310	-1437	-	65.98	4	746
4→5	28	1011	- 432	- 12	- 591	-	57.27	5	734
5→7	44	1517	- 725	+121	- 671	-	52.21	7	855
7→8	16	546	- 271	+220	- 55		50.37	8	1075
8→10	56	1862	- 705	-558	-1715		62.14	10	517
2→10	180	6644	-2714	-539	-4469		59.15		

TABLE 34. LAKE ERIE CENTRAL BASIN
TOTAL PHOSPHORUS BUDGET (METRIC TONS)
APRIL 25-NOVEMBER 1, 1974

Cruise Interval		In From			Out to E.B.	Change in Water Mass	Net Settling	Net Regeneration	Retained %	In the Water Mass	
Cruise No.	Days	W.B.	Point Sources	Diffuse Sources						Cruise No.	Metric Tons
										2	5247
2→4	36	+581	+206	+198	-372	-218	- 831	-	62.23	4	5030
4→5	28	+432	+147	+ 17	-198	-501	- 899	-	66.78	5	4528
5→7	44	725	+217	+ 33	-252	-323	-1046	-	74.15	7	4205
7→8	16	+271	+ 81	+ 2	- 72	+2005	-	+1723	79.66	8	6209
8→10	56	+705	+262	+ 8	-371	-163	- 767	-	61.95	10	6046
2→10	180	+2714	+913	+258	+1265	+800	-1820	-	67.44		

central basin during the period from cruises 2-10. During the 1974 cruise season, 69.8 percent of the external loading to the central basin originated from the western basin, while the remaining loading was contributed by diffuse and point sources. The combined western and central basin budgets (Table 35) showed an estimated 83.8 percent of the total external phosphorus loading was retained in the two basins.

1975 BUDGET

The 1975 cruise season extended over 226 days, or 62 percent of the year, our most extensive measurement program in terms of parameters and the amount of data collected. Since the data included SRP and TP as well as TSP and PP, the phosphorus budget for 1975 has been elaborated.

The total phosphorus budget for the western basin is presented in Table 36. From cruises 1 to 2 the total external loading to the western basin was 2,206 metric tons (43.3 metric tons/day), which represented 26 percent of the total yearly external phosphorus loading during the 1975 cruise season. One thousand two hundred ten metric tons, or 54.8 percent of the external loading was discharged into the central basin, while 45.2 percent was considered to have settled in the western basin. The large amount of phosphorus settled (1,574 m tons) from cruises 1 to 2 was attributed to the large fraction of particulate phosphorus entering the western basin during high spring tributary flows and to resuspended sediments mixed into the water mass during spring storms. The external phosphorus loading decreased to a low of 34.6 metric tons/ day during cruises 5 to 6. From cruises 2 through 5, the changes in the quantity of P in the water mass and the quantities of P settled were erratic. This was attributed to the meteorological conditions during the 1975 cruise season and possible anoxic regeneration from sediments by the mechanisms discussed in connection with the 1973 western basin total phosphorous budget. Fifty-three percent of the total external phosphorus loading was retained in the western basin in the 1975 season.

The 1975 total phosphorus budget for the central basin (Table 37) was significantly different from 1973 and 1974. The average total phosphorus loading to the central basin in 1974 was 21.6 metric tons/ day and in 1975, 24.8 metric tons/day. This difference was attributed to the fraction of total phosphorus loading retained in the western basin: 59 percent in 1974 and 53.1 percent in 1975. The 1975 average external loading decreased from a spring high of 31.7 metric tons/day (cruise 1 to 2) to a summer low of 20.0 metric tons/day (cruise 3 to 4). During the late fall, the external loading increased slightly to 23.9 metric tons/day.

TABLE 35. LAKE ERIE WESTERN PLUS CENTRAL BASIN TOTAL PHOSPHORUS BUDGET (METRIC TONS) APRIL 25-NOVEMBER 1, 1974

Cruise Interval		In	Out to E.B.	Change in Water Mass	Net Settling	Net Regeneration	Retained %	In the Water Mass	
Cruise No.	Days							Cruise No.	Metric Tons
								2	6303
2 → 4	36	2112	-372	-528	-2268	-	82.39	4	5776
4 → 5	28	1175	-198	-513	-1490	-	83.15	5	5262
5 → 7	44	1767	-252	-202	-1717	-	85.74	7	5060
7 → 8	16	629	- 72	+2225	-	+1668	88.55	8	7285
8 → 10	56	2132	-371	-721	-2482	-	82.60	10	6564
2 → 10	180	7815	-1265	+261	-6289	-	83.81		

TABLE 36. LAKE ERIE WESTERN BASIN
TOTAL PHOSPHORUS BUDGET (METRIC TONS)
MARCH 27-DECEMBER 14, 1975

Cruise Interval								In the Water Mass	
Cruise No.	Days	In to W.B.	Out to C.B.	Change in Water Mass	Net Settling	Net Regeneration	Retained %	Cruise No.	Metric Tons
								1	1338
1 ⟶ 2	51	+2206	-1210	-578	-1574	-	45.15	2	760
2 ⟶ 3	33	+1305	- 504	+325	- 476	-	61.38	3	1085
3 ⟶ 4	49	+1721	- 686	-193	-1228	-	60.14	4	893
4 ⟶ 5	28	+1044	- 447	+105	- 492	-	57.18	5	997
5 ⟶ 6	65	+2251	-1153	-163	-1261	-	48.78	6	835
1 ⟶ 6	226	+8527	-4000	-504	-5031		53.09		

TABLE 37. LAKE ERIE CENTRAL BASIN TOTAL PHOSPHORUS BUDGET (METRIC TONS) MARCH 27-DECEMBER 14, 1975

Cruise Interval		In From								In the Water Mass	
Cruise No.	Days	W.B.	Point Sources	Diffuse Sources	Out to E.B.	Change in Water Mass	Net Settling	Net Regeneration	Retained %	Cruise No.	Metric Tons
										1	7101
1⟶2	51	+1210	+ 277	+131	- 531	-2572	-3659		67.18	2	4529
2⟶3	33	+ 504	+ 160	+ 66	- 245	+ 386	- 99		66.44	3	4915
3⟶4	49	+ 686	+ 231	+ 64	- 297	- 27	- 711		69.72	4	4888
4⟶5	28	+ 447	+ 151	+123	- 206	+1246		+ 731	71.43	5	6134
5⟶6	65	+1153	+ 312	+ 85	- 781	+3489		+2719	49.61	6	9623
1⟶6	226	+4000	+1131	+469	-2060	+2522	-1019		63.21		

The central basin net settling from cruises 1 to 2 was 3,659 metric tons, which was more than twice the total phosphorus loading during this period. The source of the large quantity of P settled was attributed to the particulate phosphorus resuspended during the winter and early spring storms plus particulate phosphorus which entered from the western basin and tributaries. The relatively small quantity of phosphorus settled during the cruise 2 to 3 period was due to the scarcity of particulate matter in the water column at this time. The epilimnion concentrations of PP, chlorophyll a, and POC were the lowest encountered in 1975. During this period the central basin hypolimnion concentration of total phosphorus was nearly twice the concentration of the epilimnion, due to settling PP concentrating in the hypolimnion. The period from cruise 2 to 3 coincided with the decline of the vernal diatom pulse and should have been accompanied by considerable settling. If the rate of phosphorus re-entry into the water from the sediments is balanced by the sedimentation rate of phosphorus from the plankton, these quantities will not appear in the phosphorus net budget, resulting in apparent low net settling. During cruise period 4 to 5 the net regeneration of 731 metric tons of P was considered to be a result of anoxic hypolimnion regeneration. The small 1975 anoxic regeneration coincided with the small anoxic hypolimnion area of 400 km^2 compared with the larger anoxic hypolimnion, 11,270 km^2 and 10,250 km^2 in 1973 and 1974 respectively. The area of anoxic hypolimnion in 1975 was suspected to have been underestimated due to reoxygenation of the hypolimnion during cruise 4. Nevertheless, the relationship of anoxic phosphorus regeneration to the anoxia was apparent.

The large amount of total phosphorus re-entry into the water mass from cruises 5 to 6 was attributed to physical regeneration. The November and December storms as well as convection currents caused by rapid cooling of surface water were responsible for resuspension of particulate and sediment interstitial water. Since large quantities of phosphorus were regenerated by physical processes, an attempt was made to estimate the net quantities resuspended in water during cruises 5 and 6. Concentrations, ratios, and quantities of chlorophyll a, pheopigment, particulate organic carbon and PP used for the estimates are presented in the Chlorophyll section. It was estimated that approximately 38 percent of the total particulate organic carbon in the water was resuspended from the sediment. Approximately 50 percent of the total particulate phosphorus in the central basin water was estimated to have been resuspended from sediments, of which approximately 18 percent of the resuspended particulate phosphorus was in the inorganic form.

The 1975 central basin phosphorus budget showed a total loading (external plus internal) of 9,050 metric tons, of which 731 metric tons, or 8.1 percent, was attributed to anoxic regeneration and 2,719 metric tons, or 30.0 percent, to oxic regeneration. Of the 5,600 metric tons of P contributed by external loading, 3,540 metric tons, or 63.2 percent, were retained in the central basin.

The 1975 western plus central basin total phosphorus budget (Table 38) showed a total phosphorus loading (external plus internal) of 11,824 metric tons, from which 239 metric tons, or 20 percent, was attributed to net anoxic regeneration and 1,450 metric tons, or 12.2 percent, was attributed to net physical regeneration. It was determined that 8,064 metric tons, or 79.7 percent, of the 10,127 metric tons of external loading were retained in both basins. When the 1975 western plus central basin total phosphorus budget was extended over the whole year it was obvious that the anoxic regeneration accounted for considerably less than 2.0 percent of the external plus internal loading. This was a small quantity compared to the total phosphorus loading.

Budgets of Phosphorus Forms

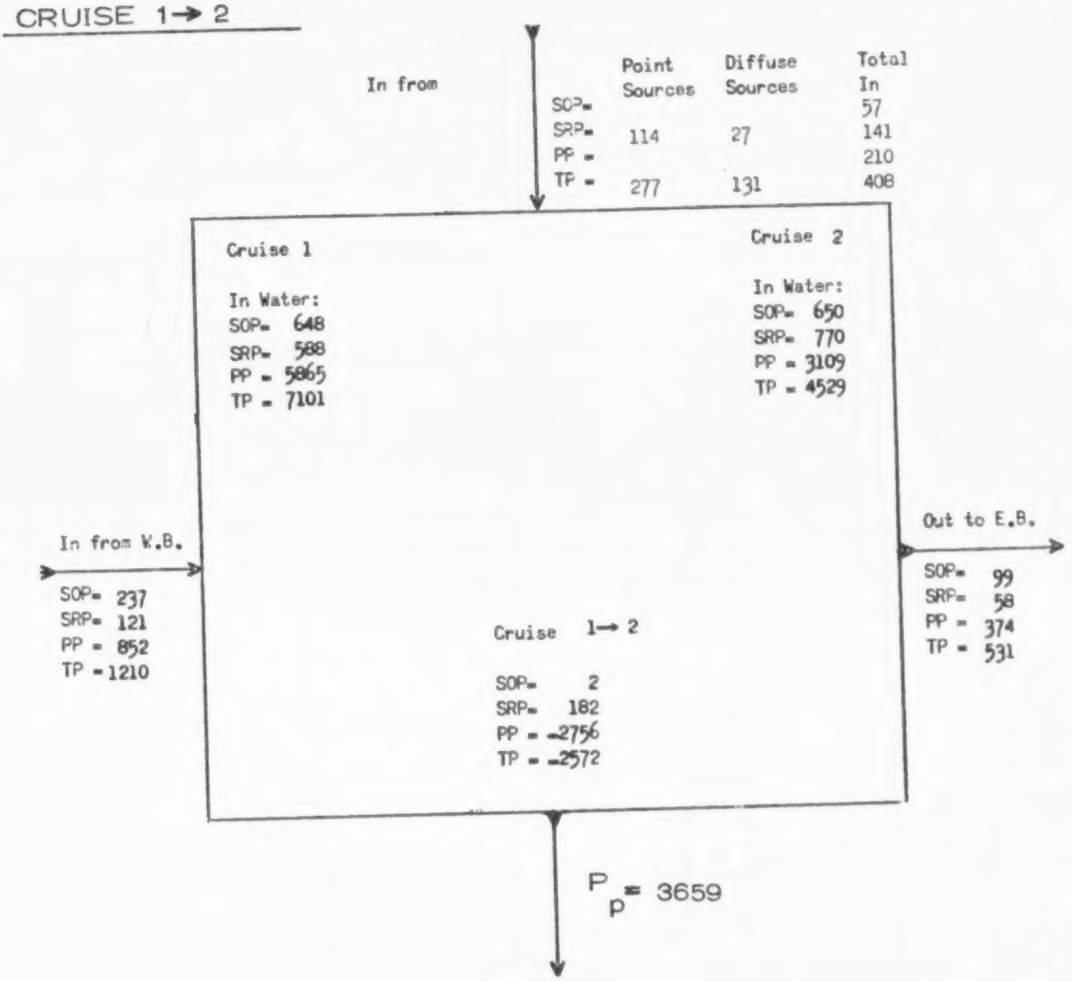
The forms of P (SRP, SOP and PP) were used to develop a budget for each cruise in 1975 (Tables 39-45). The budgets show the transport of P between compartments, the transformations of one P form to another and some mechanisms of the transformation and transport. On Tables 39, 41, 43, 44, 45, 46, and 47, the tabulated values showing the various forms of P appear with a plus or minus sign in the imbalance column. A phosphorus form appearing with a plus indicates that a transformation from that phosphorus form to another has occurred.

From cruises 1 to 2, a net imbalance of SRP and SOP of +215 metric tons appeared and was attributed to biological uptake during that period. It was conjectured that through a net assimilation of soluble reactive and soluble organic phosphorus by living organisms, these soluble forms of P were converted to particulate phosphorus. A similar situation was observed from cruises 2 to 3 when 360 metric tons of SRP + SOP were considered to have been converted to PP. The cruise 2 to 3 ipilimnion-hypolimnion budget indicated that assimilation occurred primarily in the epilimnion. This assimilation of 360 metric tons of SRP + SOP, with the accompanied 598-metric-ton increase of PP, indicated a considerable increase in biological activity from the cruise 1 to 2 interval to the 2 to 3 interval. An increase in corrected chlorophyll *a* accompanied the conversion of SRP + SOP to PP during the cruise 2 to 3 interval.

TABLE 38. LAKE ERIE WESTERN PLUS CENTRAL BASIN TOTAL PHOSPHORUS BUDGET (METRIC TONS) MARCH 27-DECEMBER 14, 1975

Cruise Interval								In the Water Mass	
Cruise No.	Days	In	Out to E.B.	Change In Water Mass	Net Settling	Net Regeneration	Retained %	Cruise No.	Metric Tons
								1	8439
1⟶2	51	+2614	- 531	-3150	- 5233		79.69	2	5289
2⟶3	33	+1531	- 245	+ 711	- 575		84.00	3	6000
3⟶4	49	+2016	- 297	- 220	- 1939		85.27	4	5781
4⟶5	28	+1318	- 206	+1351		+ 239	84.37	5	7132
5⟶6	65	+2648	- 781	+3325		+ 1458	70.51	6	10458
1⟶6	226	10127	-2060	+2017	- 6050		79.66		

TABLE 39. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGET, METRIC TONS


CRUISE 1→ 2
In from
Point Sources
Diffuse Sources
Total In
SOP= 57
SRP= 114 27 141
PP = 210
TP = 277 131 408
Cruise 1
In Water:
SOP= 648
SRP= 588
PP = 5865
TP = 7101
Cruise 2
In Water:
SOP= 650
SRP= 770
PP = 3109
TP = 4529
In from W.B.
SOP= 237
SRP= 121
PP = 852
TP = 1210
Out to E.B.
SOP= 99
SRP= 58
PP = 374
TP = 531
Cruise 1→ 2
SOP= 2
SRP= 182
PP = -2756
TP = -2572
P_p = 3659

	PP	SOP	SRP	SOP+ SRP	TP
In from W.B.	+852	+237	+121	+358	+1210
In from Point & Diffuse Sources	+210	+ 57	+141	+198	+ 408
Out to E.B.	-374	- 99	- 58	-157	- 531
Accumulated in Water	-2756	+ 2	+182	+184	-2572
Settled	-3659	–	–	–	-3659
Imbalance	-215	+193	+ 22	+215	0

TABLE 40. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGET, METRIC TONS

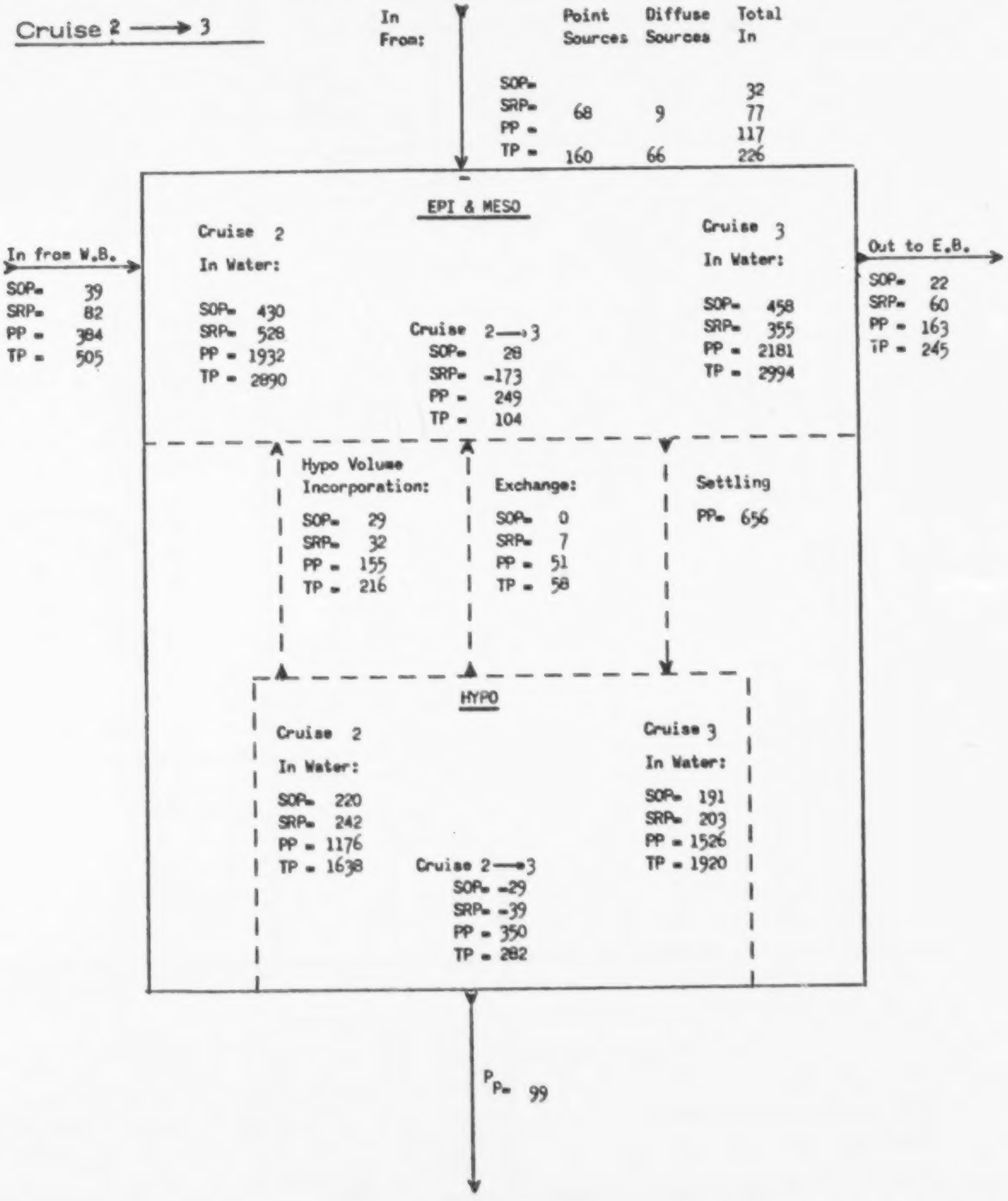

Cruise 2 → 3
In From:
Point Sources
Diffuse Sources
Total In
SOP= 32
SRP= 68 9 77
PP = 117
TP = 160 66 226
EPI & MESO
In from W.B.
SOP= 39
SRP= 82
PP = 384
TP = 505
Cruise 2
In Water:
SOP= 430
SRP= 528
PP = 1932
TP = 2890
Cruise 2 → 3
SOP= 28
SRP= -173
PP = 249
TP = 104
Cruise 3
In Water:
SOP= 458
SRP= 355
PP = 2181
TP = 2994
Out to E.B.
SOP= 22
SRP= 60
PP = 163
TP = 245
Hypo Volume Incorporation:
SOP= 29
SRP= 32
PP = 155
TP = 216
Exchange:
SOP= 0
SRP= 7
PP = 51
TP = 58
Settling
PP= 656
HYPO
Cruise 2
In Water:
SOP= 220
SRP= 242
PP = 1176
TP = 1638
Cruise 2 → 3
SOP= -29
SRP= -39
PP = 350
TP = 282
Cruise 3
In Water:
SOP= 191
SRP= 203
PP = 1526
TP = 1920
PP= 99

TABLE 41. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGETS, METRIC TONS CRUISE 2-3

	PP	SOP	SRP	SOP& SRP	TP
EPILIMNION AND MESOLIMNION					
In from W.B.	+384	+39	+ 82	+121	+505
In from Point & Diffuse Sources	+117	+32	+ 77	+109	+226
Loss or Gain of Volume	+155	+29	+ 32	+ 61	+216
Exchange	+ 51	0	+ 7	+ 7	+ 58
Out to E.B.	−163	−22	− 61	− 83	−246
Settled	−656	−	−	−	−656
Accumulated in Water	+249	+28	−173	−145	+104
Imbalance	−360	+50	+310	+360	0
HYPOLIMNION					
In from EPI	+656	−	−	−	+656
Loss or Gain of Volume	−155	−29	− 32	− 61	−216
Exchange	− 51	−	− 7	− 7	− 58
Settled	− 99	−	−	−	− 99
Accumulated in Water	+350	−29	− 39	− 68	+282
Imbalance	0	0	0	0	0
TOTAL					
In from W.B.	+384	+39	+ 82	+121	+505
In from Point & Diffuse Sources	+117	+32	+ 77	+109	+226
Out to E.B.	−163	−22	− 60	− 82	−245
Accumulated in Water	+598	−	−212	−212	+387
Settled	− 99	−	−	−	− 99
Imbalance	−360	+49	+311	+360	0

TABLE 42. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGET, METRIC TONS

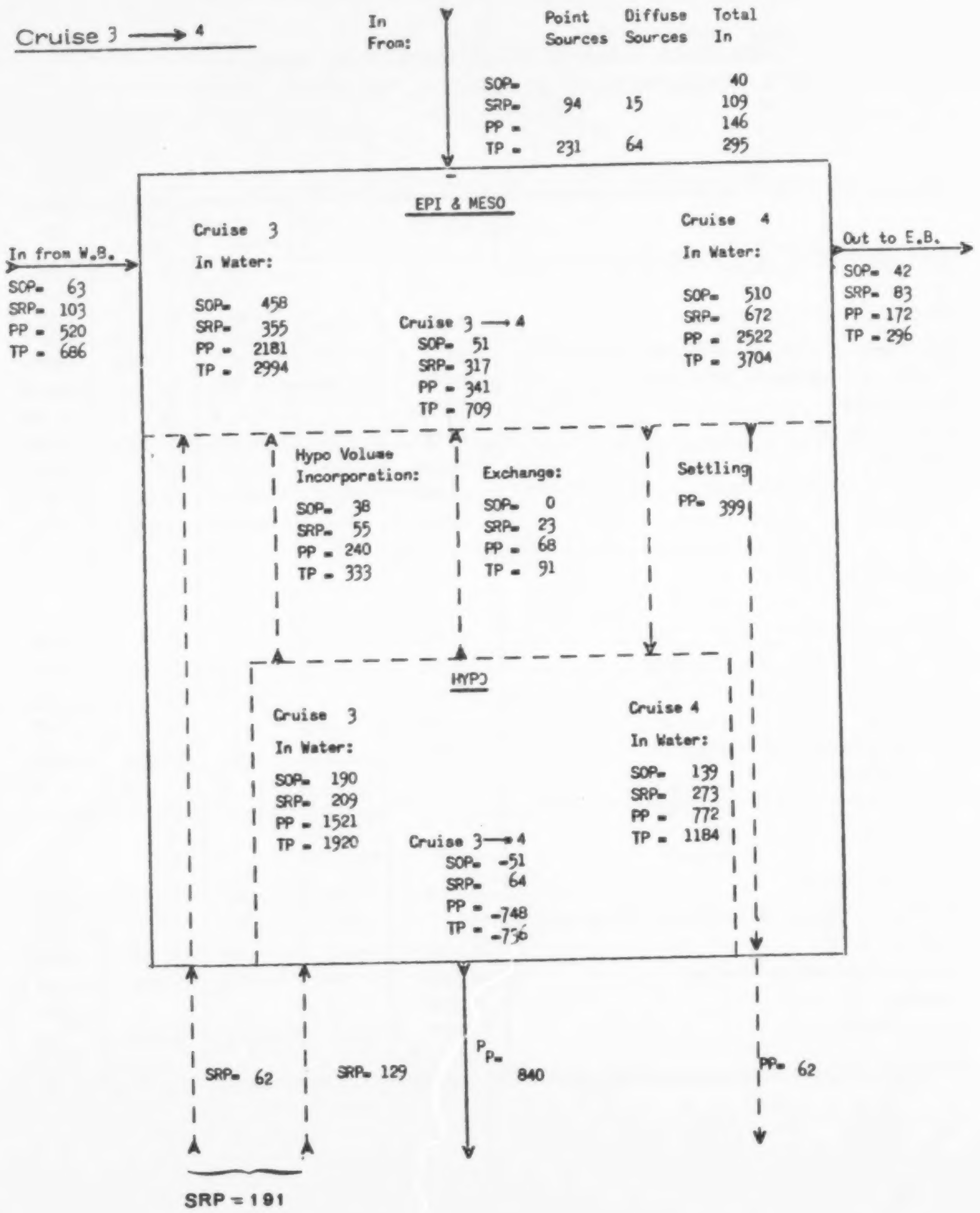

Cruise 3 → 4
In From:
Point Sources
Diffuse Sources
Total In
SOP= 40
SRP= 94 15 109
PP = 146
TP = 231 64 295
EPI & MESO
Cruise 3
In Water:
SOP= 458
SRP= 355
PP = 2181
TP = 2994
Cruise 3 → 4
SOP= 51
SRP= 317
PP = 341
TP = 709
Cruise 4
In Water:
SOP= 510
SRP= 672
PP = 2522
TP = 3704
In from W.B.
SOP= 63
SRP= 103
PP = 520
TP = 686
Out to E.B.
SOP= 42
SRP= 83
PP = 172
TP = 296
Hypo Volume Incorporation:
SOP= 38
SRP= 55
PP = 240
TP = 333
Exchange:
SOP= 0
SRP= 23
PP = 68
TP = 91
Settling
PP= 399
HYPO
Cruise 3
In Water:
SOP= 190
SRP= 209
PP = 1521
TP = 1920
Cruise 3 → 4
SOP= -51
SRP= 64
PP = -748
TP = -736
Cruise 4
In Water:
SOP= 139
SRP= 273
PP = 772
TP = 1184
SRP= 62
SRP= 129
PP= 840
PP= 62
SRP = 191

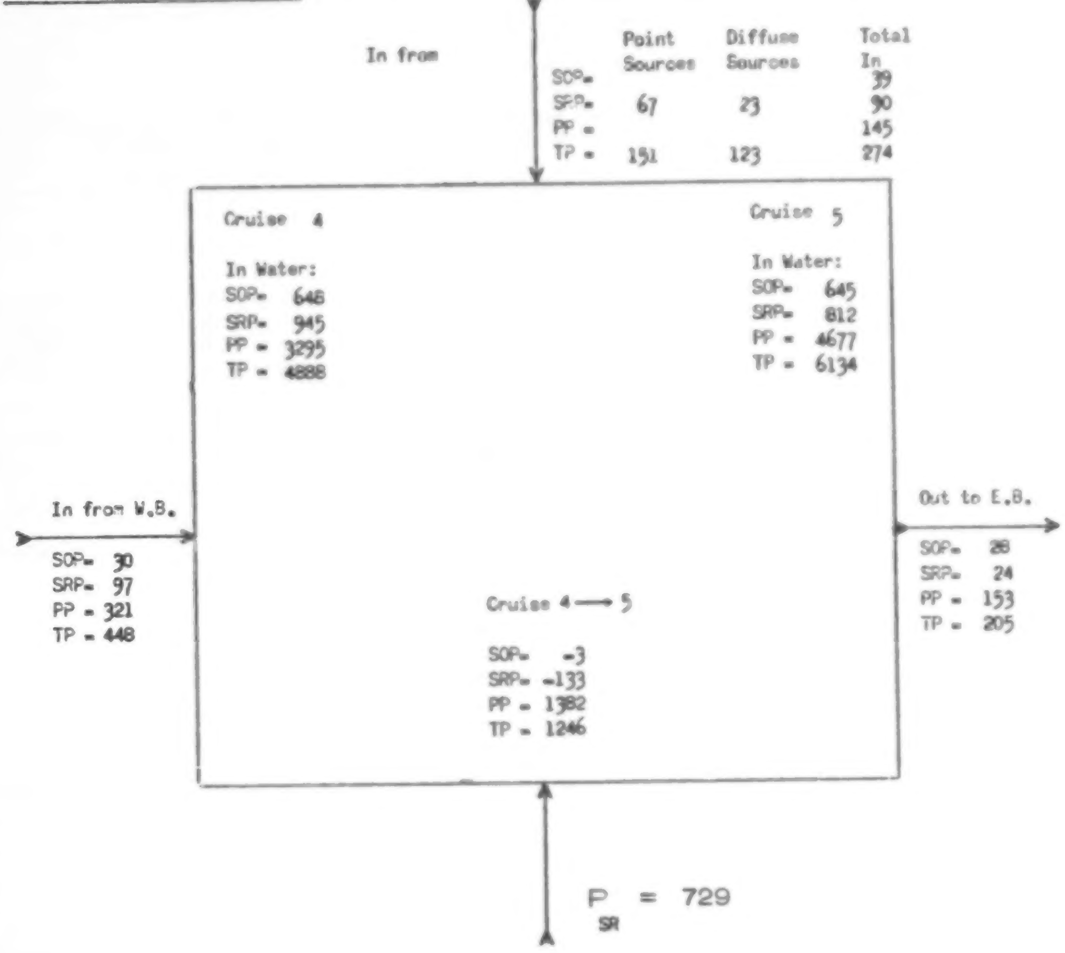
TABLE 43. LAKE ERIE CENTRAL BASIN
1975 PHOSPHORUS BUDGETS, METRIC TONS
CRUISE 3-4

	PP	SOP	SRP	SOF& SRP	TP
EPILIMNION AND MESOLIMNION					
In from W.B.	+520	+63	+103	+166	+686
In from Point & Diffuse Sources	+146	+40	+109	+149	+295
Loss or Gain of Volume	+240	+38	+ 55	+ 93	+333
Exchange	+ 68	–	+ 23	+ 23	+ 91
Out to E.B.	–172	–42	– 83	–125	–296
Settled or Regenerated	-399^{-62*}	–	+ 62*	+62*	–399
Accumulated in Water	+341	+51	+317	+368	+710
Imbalance	–	+48	– 48	–	–
HYPOLIMNION					
In from EPI	+399	–	–	–	+399
Loss or Gain of Volume	–240	–38	– 55	– 93	–333
Exchange	– 68	–	– 23	– 23	– 91
Settled or Regenerated	–840	–	+129	+129	–711
Accumulated in Water	–749	–51	+ 64	+ 13	–736
Imbalance	–	+13	– 13	–	–
TOTAL					
In from W.B.	+520	+63	+103	+166	+686
In from Point & Diffuse Sources	+146	+40	+109	+149	+295
Out to E.B.	–172	–42	– 83	–125	–297
Accumulated in Water	–407	0	+381	+381	– 26
Settled or Regenerated	–901	–	$+129^{+62*}$	$+129^{+62*}$	–710
Imbalance	–	+61	– 61	–	–

*Regenerated from and settled to unstratified areas.

TABLE 44. LAKE ERIE CENTRAL BASIN
1975 PHOSPHORUS BUDGET, METRIC TONS

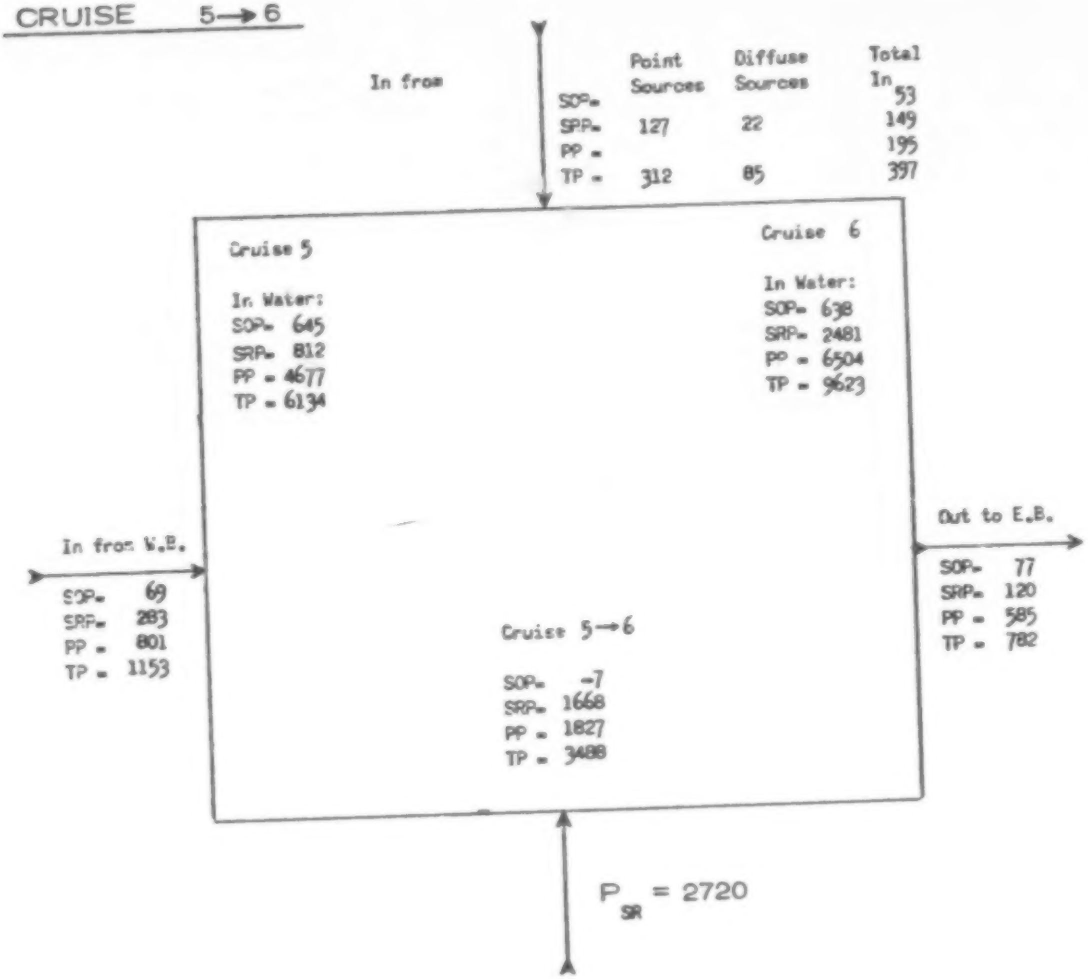
CRUISE 4→5


In from
Point Sources
Diffuse Sources
Total In
SOP = 39
SRP = 67 23 90
PP = 145
TP = 151 123 274
Cruise 4
In Water:
SOP = 648
SRP = 945
PP = 3295
TP = 4888
Cruise 5
In Water:
SOP = 645
SRP = 812
PP = 4677
TP = 6134
In from W.B.
SOP = 30
SRP = 97
PP = 321
TP = 448
Out to E.B.
SOP = 28
SRP = 24
PP = 153
TP = 205
Cruise 4 → 5
SOP = -3
SRP = -133
PP = 1382
TP = 1246
P SR = 729

	PP	SOP	SRP	SOP + SRP	TP
In from W.B.	+ 321	+ 30	+ 97	+ 127	+ 448
In from Point & Diffuse Sources	+ 145	+ 39	+ 90	+ 129	+ 274
Out to E.B.	− 153	− 28	− 24	− 52	− 205
Accumulated in Water	+1382	− 3	− 133	− 136	+1246
Settled or Regenerated			+ 729	+ 729	+ 729
Imbalance	−1069	+ 44	+1025	+1069	0

TABLE 45. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGET, METRIC TONS

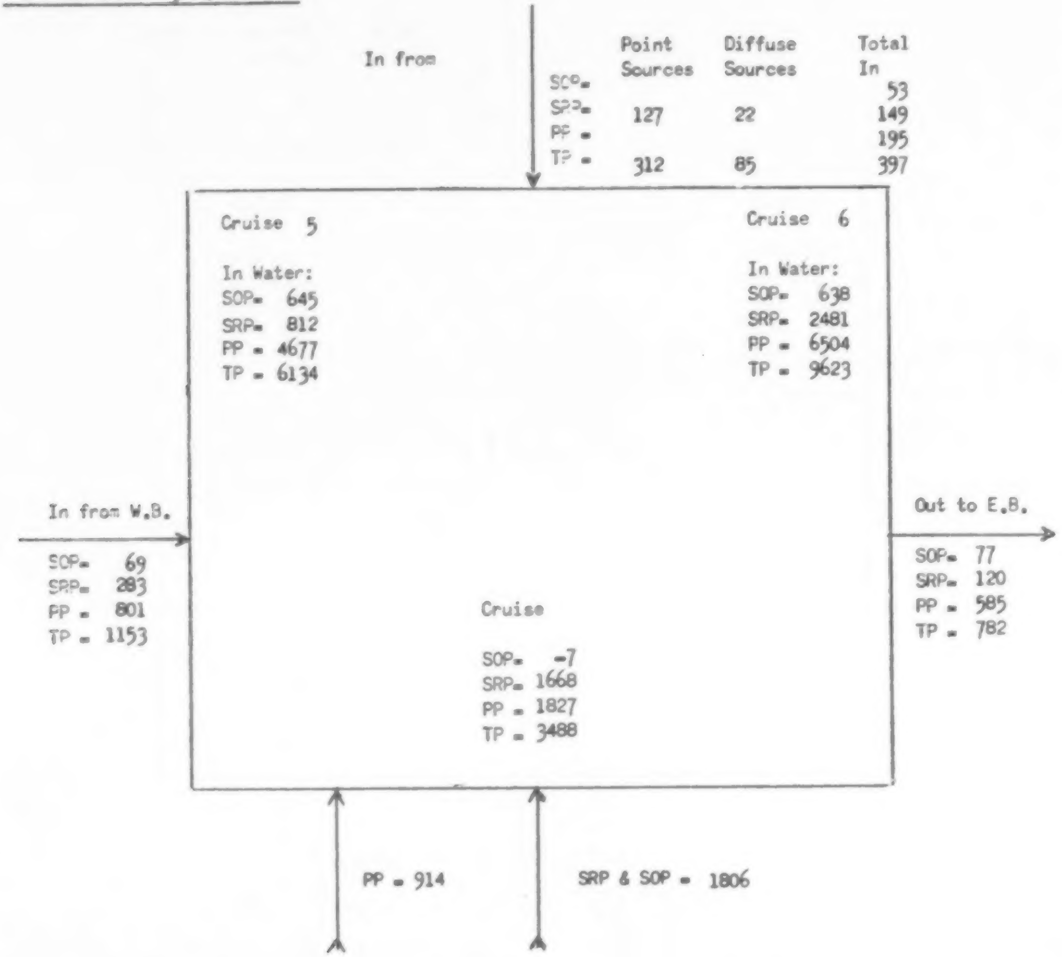
CRUISE 5→6


In from
Point Sources
Diffuse Sources
Total In
SOP= 53
SRP= 127 22 149
PP = 195
TP = 312 85 397
Cruise 5
In Water:
SOP= 645
SRP= 812
PP = 4677
TP = 6134
Cruise 6
In Water:
SOP= 638
SRP= 2481
PP = 6504
TP = 9623
In from W.B.
SOP= 69
SRP= 283
PP = 801
TP = 1153
Out to E.B.
SOP= 77
SRP= 120
PP = 585
TP = 782
Cruise 5→6
SOP= -7
SRP= 1668
PP = 1827
TP = 3488
P_{SR} = 2720

	PP	SOP	SRP	SOP+ SRP	TP
In from W.B.	+801	+69	+283	+352	+1153
In from Point & Diffuse Sources	+195	+53	+149	+202	+ 397
Out to E.B.	-585	-77	-120	-197	- 782
Accumulated in Water	+1827	- 7	+1668	+1661	+3488
Settled orRegenerated	?		+2720	+2720	+2720
Imbalance	-1416	+ 52	+1364	+1416	0

TABLE 46. LAKE ERIE CENTRAL BASIN
1975 PHOSPHORUS BUDGET, METRIC TONS

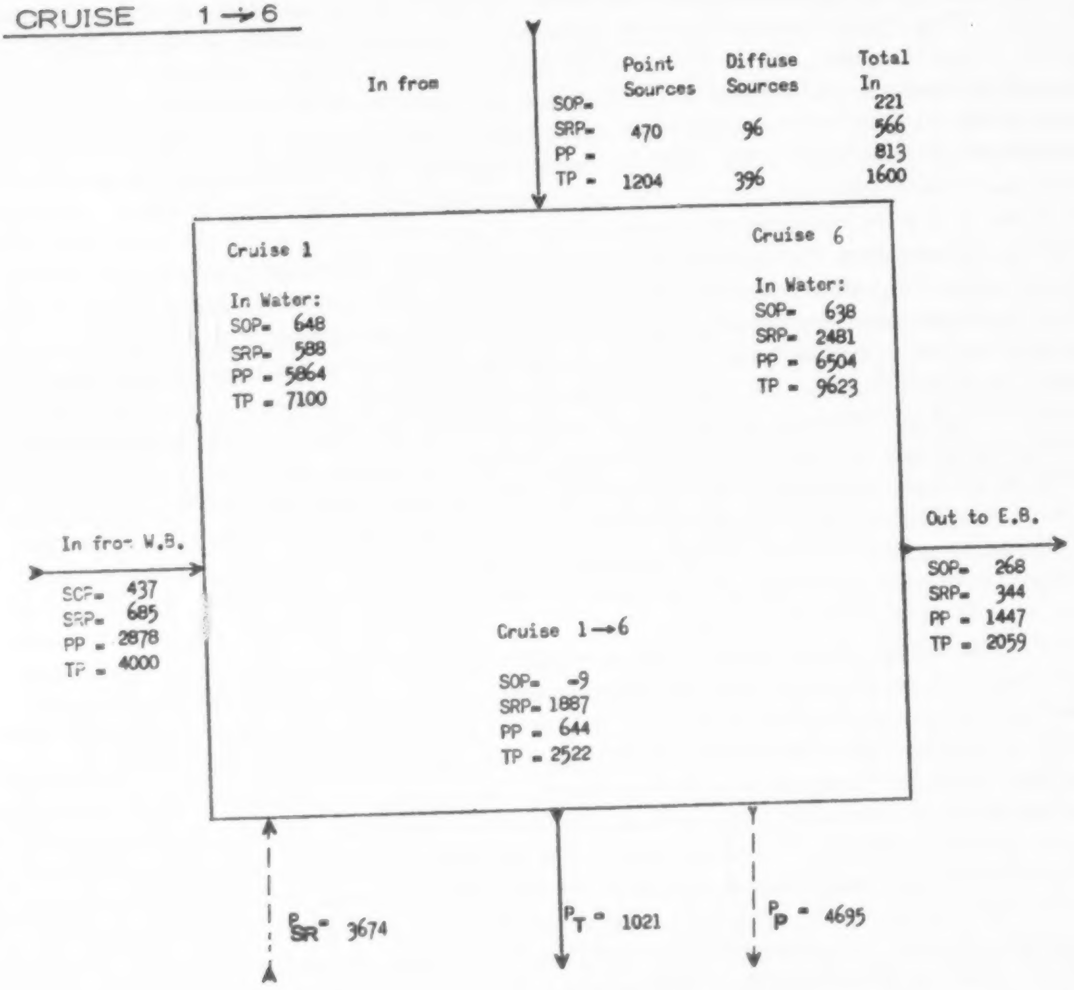
CRUISE 5→6


In from
Point Sources
Diffuse Sources
Total In
SOP = 53
SRP = 127 22 149
PP = 195
TP = 312 85 397
Cruise 5
In Water:
SOP = 645
SRP = 812
PP = 4677
TP = 6134
Cruise 6
In Water:
SOP = 638
SRP = 2481
PP = 6504
TP = 9623
In from W.B.
SOP = 69
SRP = 283
PP = 801
TP = 1153
Out to E.B.
SOP = 77
SRP = 120
PP = 585
TP = 782
Cruise
SOP = -7
SRP = 1668
PP = 1827
TP = 3488
PP = 914
SRP & SOP = 1806

	PP	SOP	SRP	SOP+ SRP	TP
In from W.B.	+ 801	+69	+ 283	+ 352	+1153
In from Point & Diffuse Sources	+ 195	+53	+ 149	+ 202	+ 397
Out to E.B.	- 585	-77	- 120	- 197	- 782
Accumulated in Water	+1827	- 7	+1668	+1661	+3488
Settledor Regenerated	+ 914		+1806	+1806	+2720
Imbalance	- 502	+52	+ 450	+ 502	0

TABLE 47. LAKE ERIE CENTRAL BASIN 1975 PHOSPHORUS BUDGET, METRIC TONS

CRUISE 1 → 6


In from
Point Sources
Diffuse Sources
Total In
SOP= 221
SRP= 470 96 566
PP = 813
TP = 1204 396 1600
Cruise 1
In Water:
SOP= 648
SRP= 588
PP = 5864
TP = 7100
Cruise 6
In Water:
SOP= 638
SRP= 2481
PP = 6504
TP = 9623
In fro- W.B.
SOP= 437
SRP= 685
PP = 2878
TP = 4000
Out to E.B.
SOP= 268
SRP= 344
PP = 1447
TP = 2059
Cruise 1→6
SOP= -9
SRP= 1887
PP = 644
TP = 2522
P_{SR} = 3674
P_T = 1021
P_P = 4695

	PP	SOP	SRP	SOP + SRP	TP
In from W.B.	+2878	+437	+ 685	+1122	+4000
In from Point & Diffuse Sources	+ 813	+221	+ 566	+ 787	+1600
Out to E.B.	-1447	-268	- 344	- 612	-2059
Accumulated in Water	+644	- 9	+1887	+1878	+2522
Settled or Regenerated	-4695		+3674	+3674	-1019
Imbalance	-3095	+399	+2694	+3095	0

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The preliminary budget calculations for the 3 to 4 cruise interval showed a net imbalance of +191 metric tons of SRP + SOP and an imbalance of -191 metric tons of PP. Since the calculated excess of 191 metric tons of SRP + SOP was assumed to be regenerated from the sediments, then the excess was thought to originate in the hypolimnion. The hypolimnion budget showed only 129 metric tons of SRP + SOP regenerated, 62 metric tons less than the total excess. The epilimnion budget indicated a deficit of 62 metric tons of SRP + SOP; consequently it was postulated that the 62 metric tons of SRP, or 32.5 percent of the total 191 metric tons regenerated, were transported from the sediment directly into the epilimnion in unstratified areas. During cruise 4 the hypolimnion covered an area of 9,600 km^2 in the central basin, while the remaining 6,490 km^2, or 40 percent, were not stratified. The relationship between the quantity of SRP regenerated in the unstratified portion of the central basin to the actual (unstratified) area appeared to substantiate the theory that SRP is directly transported from the sediments to the unstratified overlying water. The cruises 3 to 4 budget showed a net 191 metric tons of SRP + SOP regenerated and converted to PP. Comparison of the budgets for the 2 to 3 and 3 to 4 cruise periods indicates that the conversion of SRP + SOP to PP was greater during the 3 to 4 cruise interval. This increase in biological activity was also substantiated by an increase of 4.6 µg/l of uncorrected chlorophyll a during the 3 to 4 cruise interval.

The addition of 729 metric tons of SRP resulting from anoxic and oxic regeneration in the hypolimnion was shown in the budget between cruises 4 and 5. The imbalance of +1,069 metric tons of SRP + SOP was converted to PP by biological assimilation. High biological activity was also confirmed by a 2.3 µg/l increase in corrected chlorophyll a between the cruises and represented the highest chlorophyll a concentration during the 1975 cruise season. It should be mentioned that the estimated figure, 1,069 metric tons of SRP + SOP assimilated, was high. If a fraction of the net regenerated phosphorus was attributed to resuspended PP, the quantity of SRP converted to PP would have been smaller. Nevertheless, the general trend of phosphorus conversions to various forms in the central basin would be very similar even if more detailed data were available.

Table 45 shows the net phosphorus forms budget for cruises 5 to 6. The regeneration of 2,720 metric tons of SRP + SOP and the calculated quantity of SRP + SOP converted to PP appeared to be excessive. The overestimation of these quantities was primarily attributed to resuspension of PP, as was discussed as part of the 1975 total phosphorus budget. Table 46 shows the net phosphorus forms budget for cruises 5 to 6, corrected for resuspended PP. The corrected budget for cruises 5 to 6 indicated a regeneration of 1,806 metric tons of SRP with 502 metric tons of SRP + SOP converted to PP. This estimate suggests there was a considerable decrease in biological activity during the 5 to 6 cruise interval, as compared to cruises 4 to 5. A 3.1 μg/l decrease in corrected chlorophyll a concentration was further evidence of decreased biological activity.

The phosphorus forms budget for the entire 1975 season appears as Table 47. The conversion of 3,095 metric tons of SRP + SOP to PP was not corrected for resuspension of PP and, therefore, appears higher than the actual conversion.

Figures 57 and 58 show the SRP + SOP ⟶ PP conversion rates and sedimentation rates for the 1975 cruise season. Anoxic regeneration of phosphorus and peak biological activity during the cruise 4 to 5 period is apparent from both curves.

CONCLUSIONS

The 1973 through 1975 measurement of total phosphorus were compared with 1970 CCIW measurements (Table 48). The external phosphorus loadings to both the western and central basins were considerably greater during 1970. The concentrations and quantities of TP in the western basin during 1970 were not significantly greater and the quantity and concentration in the central basin was only slightly greater. The percent of TP retained in the western basin during 1970 was the greatest of the three years examined. In 1974 and 1975, 59.2 and 53.1 percent, respectively, of the western basin external TP load was retained in the basin, as compared with the 77 percent retained in 1970. The percent of the quantity of phosphorus retained in the central basin was greatest in 1974, but not much different from 1970 or 1975. The quantity of TP retained in the combined western and central basins was greatest in 1970 due to the large fraction of external loading retained in the western basin. The estimated 1970 total external loadings of P to the western and central basins used by Burns (1976) were 23,580 and 5,220 metric tons, respectively (Table 48). The updated U.S. Army Corps of Engineers (1975) estimated loadings to the western and central basins for 1970 were 17,043 and 4,501 metric tons, respectively. The revised estimates, particularly for the western basin, indicate that little change in total loading has taken place from 1970 to 1973. Based on the revised loading values for the western basin, the percent of P retained within the basin is estimated to be 61 percent, which is similar to the value for 1974 (see Overview section). The Canada Centre for Inland Waters has not recalculated the 1970 phosphorus budget based on the revised loading estimates (Noel Burns, personal communication).

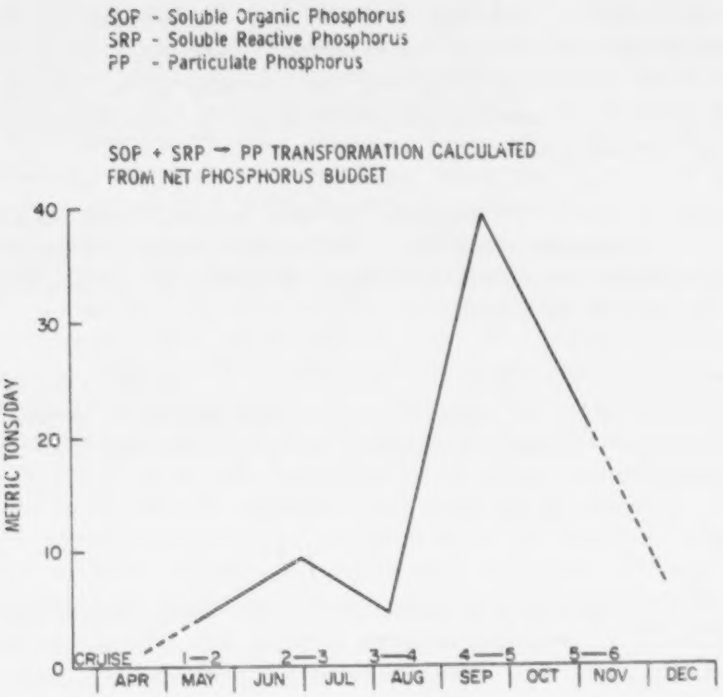

Figure 57. Lake Erie central basin - 1975, phosphorus transformation.

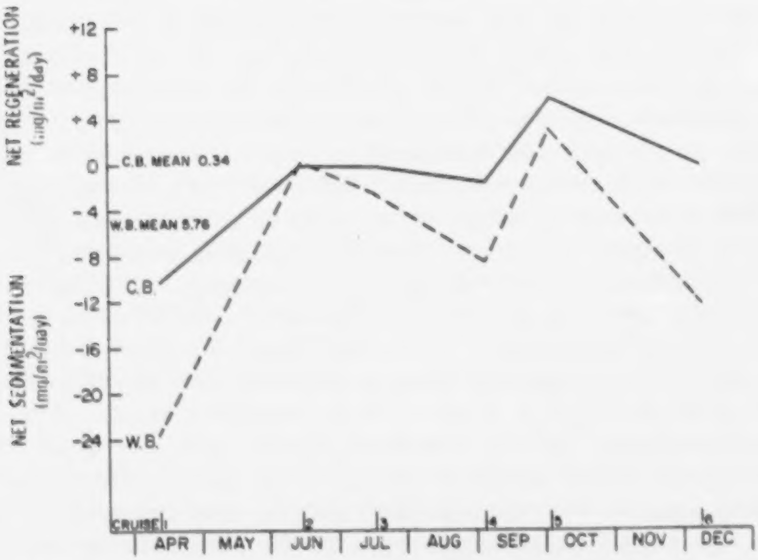

Figure 58. Regeneration and sedimentation rates of particulate phosphorus in the central and western basins of Lake Erie - 1975.

TABLE 48. LAKE ERIE WESTERN AND CENTRAL BASIN 1970-1975 MAY THROUGH SEPTEMBER (5/1-9/30) MEAN TOTAL PHOSPHORUS CONCENTRATION AND QUANTITIES, "ANOXIC" REGENERATION, EXTERNAL LOADING, AND SINK

YEAR	WESTERN BASIN				CENTRAL BASIN						W.B. + C.B.	
	Mean 5/1 - 9/30		TP External Loading M-Tons per Year	TP Retained Percent of Input	Mean 5/1 - 9/30		Area of Anoxic Hypolimnion km^2	TP Anoxic Regeneration M-Tons	TP External Loading M-Tons per Year	TP Retained Percent of Input	TP External Loading M-Tons per Year	TP Retained Percent of Input
	TP M-Tons	TP Conc. µg/l			TP M-Tons	TP Conc. µg/l						
1970	895*	38.3*	23580***	77	5500*	17.9*	6600	1900	5220**	65	28800	87.7
1973	-	-	17500	-	-	-	11270	2570	4000**	-	21500	-
1974	840	35.4	16600	59.2	5250	16.6	10250	1720	4200**	67.4	20900	83.8
1975	980	41.8	14900	53.1	5150	17.0	400	730	3850**	63.3	18800	79.7

* C.C.I.W. data recalculated with the volumes used by CLEAR for 1973, 1974 and 1975.

** Does not include TP entering from western basin.

*** Does not include TP from precipitation. The 1970 estimated phosphorus loading appears excessive.

The area of anoxia was highly variable during the study period (Table 49). In 1970 the area of anoxia was nearly half that which occurred in 1973 and 1974, but the quantities of TP in the central basin were not significantly different. This may be attributed to the extension of the anoxic period into late September 1970, while in 1973 and 1974, turnover occurred early in September. In 1973 anoxic regeneration was overestimated, since the increase in quantity of TP also included resuspended phosphorus from the sediments, attributed to stormy weather following turnover in 1973.

The 1970 and 1974 data are most comparable on the basis of sampling schedule. The quantity of phosphorus regenerated in 1970 was slightly greater than in 1974 despite the nearly twofold increase of anoxic area in 1974. As previously mentioned, this was attributed to the duration of the anoxic period.

The 1975 estimate of anoxic area and the quantity of phosphorus regenerated associated with anoxia was underestimated. During the late summer anoxic period, the hypolimnion was reoxygenated prior to turnover; so the area and the phosphorus associated with anoxia were difficult to estimate.

The 1975 central basin phosphorus budget shows that 8.1 percent of total phosphorus loading (internal plus external) was attributed to anoxic regeneration and 30.0 percent to oxic or physical regeneration (resuspension). Similar conditions were observed in 1970. In 1973 and 1974 no measurements were taken during December, but similar conditions probably existed in these years. If the 1975 western basin and central basin phosphorus budget was extended over the whole year, the percentage of total phosphorus loading (internal plus external) contributed by anoxic regeneration would decrease considerably.

The following major conclusions were reached during the course of this study:

1. The 1970, 1974 and 1975 nutrient monitoring surveys do not show significant change in concentration and quantity of phosphorus in the Lake Erie western and central basin water.

2. Physical regeneration (resuspension) appears to be the major source of internal phosphorus loading.

TABLE 49. TOTAL PHOSPHORUS "ANOXIC" REGENERATION ASSOCIATED WITH ANOXIC HYPOLIMNION LAKE ERIE WESTERN AND CENTRAL BASIN 1973, 1974 AND 1975

	External Total Phosphorus Loading (Metric Tons*)			Total Phosphorus ''Anoxic Regeneration (Tone)			
							% of External Loading
Year	W.B.	C.B.	W.B.&C.B.	W.B.	C.B.	W.B.&.C.B.	W.B.&.C.B.
1973	17500	4000	21495	0	2570	2571	12.0
1974	16600	4200	20869	0	1720	1723	8.3
1975	14900	3850	18775	0	730	731	3.9

* Corps of Engineers, Buffalo District, Data.

3. Anoxic regeneration of phosphorus was considered of secondary importance as a source of internal loading and only contributed during the late summer in the central basin.

4. During 1970-1975, the western and central basin served as phosphorus sinks.

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U.S. Army Corps of Engineers. 1975. Lake Erie water managements study, Vol. 3. U.S. Army, Corps of Eng., Buffalo Dist. Buffalo, N.Y.

SECTION 7

CHLOROPHYLL a AND PHEOPIGMENT DISTRIBUTION IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

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Center for Lake Erie Area Research
The Ohio State University

INTRODUCTION

Chlorophyll in Lake Erie's central and western basins was monitored by the Center for Lake Erie Area Research (CLEAR) from 1973 to 1975 as a portion of the Lake Erie Nutrient Study sponsored by the U.S. Environmental Protection Agency's Large Lake Research Station at Grosse Ile, Michigan (Grant No. R-802543-01). Chlorophyll pigments, along with other eutrophication indicators, were measured to determine if recent attempts to impede eutrophication by reducing nutrient loading into Lake Erie have been effective. Water samples collected on 15 general cruises during these three field seasons were analyzed for chlorophyll pigments. Sampling and analysis in Lake Erie's eastern basin was undertaken by the Great Lakes Laboratory (GLL) at Buffalo (SUNY).

The major objective of this portion of the survey was to quantify chlorophyll a and pheopigment a in the central and western basins and to observe seasonal and yearly trends of chlorophyll concentrations. Shoreline versus open lake concentrations were also examined. To analyze the data, several analyses of variance and regression models were used.

MATERIALS AND METHODS

Water samples were collected from 51 stations, 37 in the central basin and 14 in the western basin, with Niskin water bottles set in series. Depth selections were identical to those for nutrient analysis. Water was filtered through Whatman GF/C glass fiber filters to which a few drops of $MgCO_3$ suspension were added. The samples were placed in plastic petri dishes and frozen (-8°C) until analysis.

Filters were ground with a teflon homogenizer at 300 rpm for less than one minute in 4 ml of 90 percent acetone. The samples were diluted to 12 ml and placed in a dark refrigerator for 4 hours before analysis.

After 10 minutes of centrifugation at 3000 rpm, the samples were analyzed spectrophotometrically. A Varian Techtron model 635 automatic spectrophotometer in conjunction with a computer was used for sample analysis and calculations. Table 50 presents the equations used to calculate chlorophyll concentrations. Three different equations for chlorophyll *a* were used: Odum et al. (1958); SCOR/UNESCO (1966) and Lorenzen (1967), chlorophyll *a* corrected for the amount of pheopigment.

Calculations of chlorophylls *b* and *c*, and pheopigment *a* were made for all samples. In addition, the ratio of absorbances at 663 nm before and after acidification (Fo/Fa ratio, Lorenzen, 1967) was determined. An Fo/Fa ratio of 1.7 indicates that the sample contained pure chlorophyll *a*, while a ratio of 1.0 indicates that the sample was pure pheopigment *a*. Ratios falling within this range represent varying percentages of both chlorophyll *a* and pheopigment *a*. This ratio was helpful in determining the physiological condition of the phytoplankton.

The chlorophyll data are expressed as µg/l of corrected chlorophyll *a* or as metric tons of corrected chlorophyll *a*. All of the data presented were volume weighted in accordance with the procedure outlined in the overview section.

Chlorophyll Standards

Chlorophyll standards were acquired from the U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory at Cincinnati, Ohio. Comparisons of estimated concentrations by the E.P.A. and those determined by CLEAR on the Varian Techtron are as follows:

Equation		
SCOR/UNESCO	EPA	CLEAR
Chl *a*	8.40 ± 0.40	8.21 ± 0.04
Chl *b*	2.55 ± 0.20	2.85 ± 0.03
Chl *c*	1.69 ± 0.40	1.50 ± 0.02
Lorenzen		
Corrected Chl *a*	6.09 ± 1.10	5.83
pheopigment *a*	4.17 ± 1.40	4.30

TABLE 50. EQUATIONS USED FOR LAKE ERIE 1973-1975 CALCULATIONS

SCOR/UNESCO (1966)

$$\text{Chl } \underline{a}\ (\mu g/l) = 11.64(\text{O.D.}663-\text{O.D.}750)-2.16(\text{O.D.}645-\text{O.D.}750) +0.10(\text{O.D.}630-\text{O.D.}750)$$

$$\text{Chl } \underline{b}\ (\mu g/l) = 20.97(\text{O.D.}645-\text{O.D.}750)-3.94(\text{O.D.}663-\text{O.D.}750) -3.66(\text{O.D.}663-\text{O.D.}750)$$

$$\text{Chl } \underline{c}\ (\mu g/l) = 54.22(\text{O.D.}630-\text{O.D.}750)-14.81(\text{O.D.}645-\text{O.D.}750) -5.53(\text{O.D.}663-\text{O.D.}750)$$

Lorenzen (1967)

$$\text{Corrected Chl } \underline{a}\ (\mu g/l) = 26.73(\text{O.D.}663-\text{O.D.}750) -(\text{O.D.}663_{acid}-\text{O.D.}750_{acid})$$

$$\text{Pheopigment } \underline{a}\ (\mu g/l) = 26.73\times 1.7(\text{O.D.}663_{acid}-\text{O.D.}750_{acid}) -(\text{O.D.}663-\text{O.D.}750)$$

$$\text{Fo:Fa} = \text{O.D.}663-\text{O.D.}750/(\text{O.D.}663_{acid}-\text{O.D.}750_{acid})$$

Odum et al. (1958)

$$\text{Chl } \underline{a}\ (\mu g/l) = 13.4(\text{O.D.}665)$$

* All values must take into account the volume of the extract (ml), the volume of water filtered (liters) and cuvette cell length (cm). These factors must all be taken into account for the final determination. An example of a complete SCOR/UNESCO equation follows:

$$\text{Chl } \underline{a} = \frac{11.64(\text{O.D.}663-\text{O.D.}750)-2.16(\text{O.D.}645-\text{O.D.}750) +0.10(\text{O.D.}630-\text{O.D.}750)\times\text{Volume of extract}}{\text{Volume filtered (liters)} \times \text{cuvette length (cm)}}$$

O.D. = Optical Density.

Chlorophyll b was found to be slightly higher than the EPA estimate. Both chlorophylls a and c fell within the estimated range. Comparisons of corrected chlorophyll a and pheopigment a were also positive.

Measurement Errors

A single sample of chlorophyll was scanned 20 times at 750, 663, 645 and 630 nm during a 30-minute period and the results analyzed for repeatibility. Chlorophyll a concentrations had a standard deviation of 0.01 with 0.12 percent standard deviation. Chlorophyll b appeared to be the second most reliable determination with 0.02 standard deviation (0.70 percent). Chlorophyll c had a 0.04 standard deviation or 3.60 percent.

An error resulting from an inaccurate absorbance reading of 0.001 was calculated for each of the three chlorophyll absorbance maxima. A theoretical measurement error of less than one percent was calculated for chlorophylls a and b, while the estimated error for chlorophyll c was 4.4 percent. In addition the chlorophyll c value was also influenced by an error at the chlorophyll b absorbance.

Less than one percent of the chlorophyll b and c observations had negative values. It was felt that the negative concentrations resulted from errors in absorbance readings when low chlorophyll concentrations were encountered. Errors resulting from extended periods of freeze storage (greater than 60 days) for corrected chlorophyll a and pheopigment a were estimated. Due to the variability of the length of sample storage, plus the need for further investigations into the effects of storage on chlorophyll degradation and pheopigment development, no attempt was made to correct for this source of error.

RESULTS AND DISCUSSION

When analyzing the chlorophyll a data for the 1973, 1974 and 1975 seasons the major emphasis was placed on generalized and long-term effects. Due to the three-year duration of the study and lengthy intervals between sampling cruises, it was felt that this overview would yield the most useful information concerning the overall trends and regional effects since the 1970 Canada Centre for Inland Waters study (Glooschenko et al. 1974).

Sub-Basin Comparisons

Geologically, Lake Erie is divided into western, central and eastern basins by glacial moraines. The western basin is the shallowest of the three basins with a mean depth of 7.4 m and represents only 5 percent of the total lake volume. The central basin has a mean depth of 18.5 m and contains 63 percent of the total lake volume (Verber, 1950). The relationship of basin morphometry to the rate of eutrophication has been discussed by many investigators. Vollenweider (1971) demonstrated that similar nutrient loadings to a shallow lake (10 m) and to a deeper lake (100 m) would result in a greater increase in the rate of eutrophication of the shallower lake. Sakamoto (1966) also emphasized that phytoplankton production was influenced by basin depth and attributed this influence to differences in availability of light and nutrients in deep versus shallow basins.

The shallow western basin of Lake Erie is continuously supplied with nutrients from the Detroit, Maumee, Raisin and Portage Rivers as well as non-point sources. In addition to external loading, nutrients are regenerated from decomposition of organic matter, i.e. plankton. Thus the nutrient-rich western basin maintains high concentrations of chlorophyll a throughout the year.

The deeper central basin is less productive than the western basin throughout the year and especially during the summer months. Summer standing crops in deep lakes are generally smaller than they are during vernal and autumnal circulation periods (Sakamoto, 1966). This can be attributed to the accumulation of nutrients in the hypolimnion which are largely prevented from mixing with the nutrient-depleted waters of the epilimnion.

The basin effect on chlorophyll a concentrations for the western basin and the central basin was found to be of first order importance. Western-central basin ratios of corrected chlorophyll a were calculated using volume-weighted cruise averages (Table 51) in order to evaluate the difference between the basins. The average concentrations of chlorophyll a in the western basin were usually two to three times those found in the central basin. The largest basin ratios were observed during the summer months when the western basin reached its maximum chlorophyll a concentrations and the central basin its lowest. The lowest western to central basin ratios were observed in the fall and winter months. For example, during the fall of each year, chlorophyll a concentration was reduced to approximately 1.5 times that of the central basin.

TABLE 51. CORRECTED CHLOROPHYLL a (µg/l) VOLUME WEIGHTED CONCENTRATIONS, 1973-1975

Year	Cruise	Western	Central	W : C Basin Ratio
1973	17-23 July	8.34	2.40	3.48 : 1.0
	29 Aug-4 Sept	11.74	3.38	3.47 : 1.0
	14-24 October	11.95	7.87	1.52 : 1.0
	Yearly Average	10.68	4.55	2.34 : 1.0
1974	25 April-4 May	8.75	3.47	2.52 : 1.0
	1-10 June	10.03	2.63	3.81 : 1.0
	28 June-7 July	16.50	2.41	6.85 : 1.0
	12-19 August	17.14	3.82	4.49 : 1.0
	26 Aug-7 Sept	13.48	3.76	3.59 : 1.0
	21 Oct-1 Nov	14.65	9.45	1.55 : 1.0
	Yearly Average	13.43	4.26	3.15 : 1.0
1975	27-31 March	10.34	5.09	2.03 : 1.0
	21-25 April			
	9-19 June	21.07	2.71	7.78 : 1.0
	13-21 July	17.59	3.11	5.66 : 1.0
	30 Aug-5 Sept	16.31	7.72	2.11 : 1.0
	27 Sept - 6 Oct	12.34	10.05	1.23 : 1.0
	2-14 December	4.66	6.92	0.67 : 1.0
	Yearly Average	13.72	5.93	2.31 : 1.0

For more detailed chlorophyll a comparisons within the central basin, it was subdivided into eastern and western segments. The division was demarcated by a line running south from Pointe Aux Pins, Ontario to slightly east of Cleveland, Ohio (Figure 59). The eastern central basin included stations 23-29 (grids 19-31) and the western basin stations 40-54 plus stations 65 and 74 (grids 32-43). Cruise average corrected chlorophyll a concentrations for the three sub-basins were examined (Table 52). The western basin normally had the highest average chlorophyll a values ranging from 1 to 9 times the eastern central basin average concentrations, although exceptions to the west-east trend of decreasing chlorophyll a concentrations did occur. For example, in December of 1975 the western basin was observed to have lower chlorophyll a values than the eastern central basin (0.7:1.0). The western central basin generally had the second highest corrected chlorophyll a concentrations with the exception of early June 1974 and early October 1975. The three-year average corrected chlorophyll a concentrations for each station (Table 53) also substantiate the west to east trend (Figures 60 and 61). Two anomolies existed: (1) a low concentration area in the western basin east of the Detroit River mouth and (2) a high concentration area in the central basin extending from the island area eastward along the southern shore of the central basin.

Due to high and low areas of concentration within the central basin, it was further subdivided into 3 regions (Figure 62): (1) shore (s), (2) mid-lake (m) and (3) the Sandusky sub-basin (b), Thomas, et al. (1976). The average corrected chlorophyll a concentrations (µg/l) of the western basin and the designated sub-basins of the central basin for each of the three years were:

	1973	1974	1975
Western (wb)	12.05	13.45	14.80
Sandusky sub-basin (b)	6.55	9.08	9.77
Shore (s)	5.40	4.52	6.71
Mid-lake (m)	3.60	3.30	5.08

The trend throughout the three years was very consistent. Chlorophyll a was found in highest concentrations in the western basin followed by the Sandusky sub-basin and the shore area, with the mid-lake having the lowest values, as domonstrated by the three-year basin ratio:

western basin		Sandusky sub-basin		shore		mid-lake
3.37	:	2.18	:	1.36	:	1.00

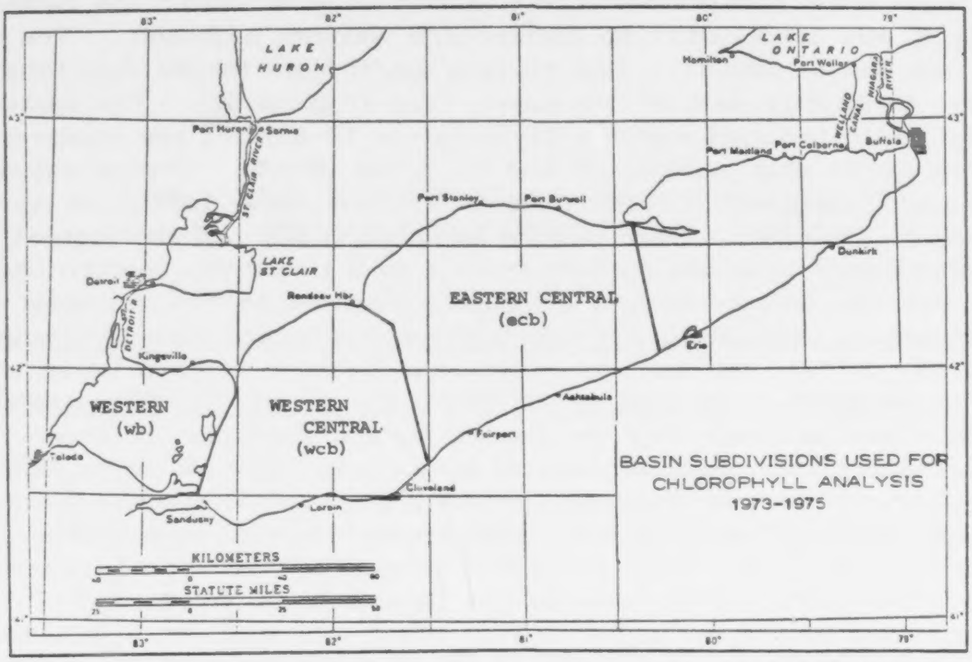

LAKE HURON
LAKE ONTARIO
Hamilton
Port Weller
WELLAND CANAL
NIAGARA RIVER
Port Huron
Sarnia
ST CLAIR RIVER
Port Maitland
Port Colborne
Buffalo
Port Stanley
Port Burwell
LAKE ST CLAIR
Detroit
DETROIT R
Dunkirk
Rondeau Hbr
EASTERN CENTRAL
(ecb)
Kingsville
Erie
WESTERN
(wb)
WESTERN
CENTRAL
(wcb)
Ashtabula
Fairport
Toledo
Cleveland
Sandusky
Lorain
BASIN SUBDIVISIONS USED FOR
CHLOROPHYLL ANALYSIS
1973-1975
KILOMETERS
STATUTE MILES
83°
82°
81°
80°
79°
43°
42°
41°

Figure 59. Basin subdivisions used for chlorophyll analysis 1973-1975.

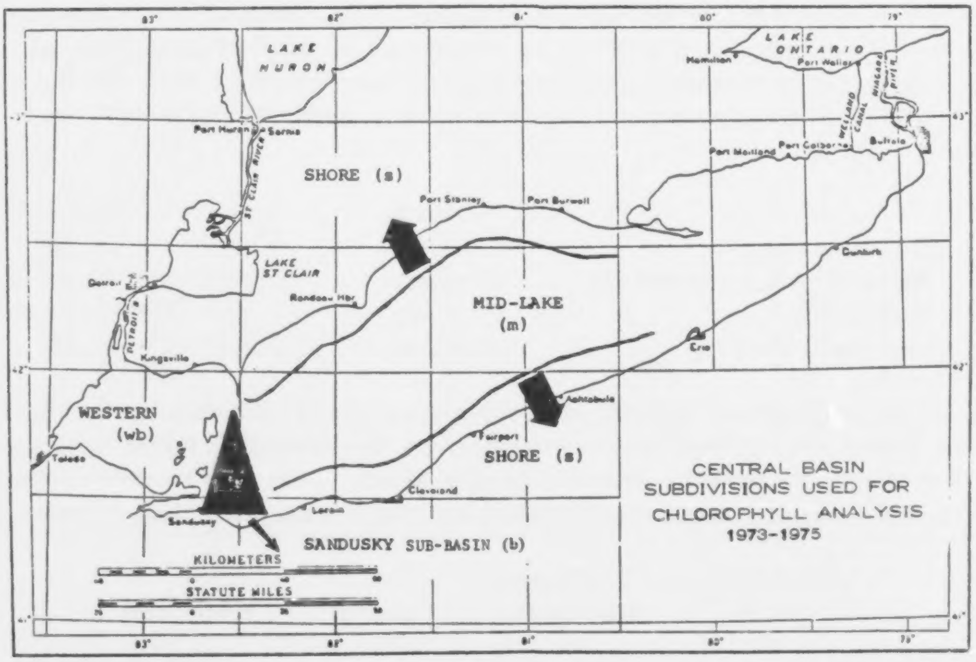

LAKE HURON
LAKE ONTARIO
Hamilton
Port Weller
WELLAND CANAL
NIAGARA RIVER
Port Huron
Sarnia
ST CLAIR RIVER
Port Maitland
Port Colborne
Buffalo
SHORE (s)
Port Stanley
Port Burwell
LAKE ST CLAIR
Detroit
DETROIT R
Dunkirk
Rondeau Hbr
MID-LAKE
(m)
Kingsville
Erie
WESTERN
(wb)
Ashtabula
Fairport
SHORE (s)
Toledo
Cleveland
Sandusky
Lorain
SANDUSKY SUB-BASIN (b)
CENTRAL BASIN
SUBDIVISIONS USED FOR
CHLOROPHYLL ANALYSIS
1973-1975
KILOMETERS
STATUTE MILES
83°
82°
81°
80°
79°
43°
42°
41°

Figure 60. Central basin subdivisions used for chlorophyll analysis, 1973-1975.

TABLE 52. CORRECTED CHLOROPHYLL a (μg/l) VOLUME WEIGHTED CONCENTRATIONS, 1973-1975

Cruise	Western Basin	Central Basin West	Central Basin East	Basin Ratio WB : WCB : ECB
1973				
Late July	8.34	3.69	1.75	4.77 : 2.05 : 1.0
Late August	11.74	5.22	2.37	4.95 : 2.20 : 1.0
Mid October	11.95	8.27	7.65	1.56 : 1.08 : 1.0
1974				
Early May	8.75	4.32	3.01	2.91 : 1.44 : 1.0
Early June	10.03	2.03	2.54	3.95 : 0.80 : 1.0
Early July	16.50	3.74	1.68	9.82 : 2.23 : 1.0
Mid August	17.14	5.77	2.76	6.21 : 2.09 : 1.0
Early September	13.48	5.44	2.84	4.75 : 1.92 : 1.0
Late October	14.65	12.56	7.74	1.89 : 1.62 : 1.0
1975				
April	10.34	6.28	4.44	2.33 : 1.41 : 1.0
Mid June	21.07	3.28	2.40	8.78 : 1.37 : 1.0
Mid July	17.59	4.49	2.36	7.45 : 1.90 : 1.0
Early September	16.31	10.26	6.33	2.58 : 1.62 : 1.0
Early October	12.34	9.89	10.14	1.22 : 0.98 : 1.0
Early December	4.66	7.47	6.62	0.70 : 1.13 : 1.0

TABLE 53. CORRECTED CHLOROPHYLL a (µg/l) STATION MEANS FOR THE 15 CRUISES, 1973-1975

Station	Means	Standard Deviation	Number of Measurements	Station	Means	Standard Deviation	Number of Measurements
23	5.44	4.28	46	50	8.36	3.63	43
24	3.94	3.13	46	51	7.35	4.16	46
25	3.65	2.76	50	52	8.53	6.38	46
26	3.54	2.75	47	53	10.53	5.80	45
27	3.93	3.06	51	54	10.16	6.98	45
28	4.55	2.89	49	55	11.43	6.60	42
29	4.73	2.92	45	56	11.98	4.57	45
30	4.45	3.51	54	57	14.80	13.31	44
31	3.56	2.86	52	58	13.66	8.67	39
32	3.72	2.52	52	59	12.93	7.63	45
33	4.24	3.23	45	60	14.30	12.71	45
34	6.05	4.13	48	61	7.47	4.69	41
35	6.37	3.98	43	65	9.21	5.57	46
36	4.01	3.02	53	66	13.29	5.36	39
37	3.41	2.25	51	67	11.15	8.10	46
38	3.96	2.41	52	68	11.51	8.17	45
39	4.26	3.26	46	69	14.42	7.62	20
40	5.21	2.97	49	70	24.60	14.93	32
41	5.81	3.98	51	71	2.63	1.72	10
42	3.80	3.07	51	72	4.04	3.53	10
43	4.46	3.60	52	73	3.87	3.50	51
44	9.03	4.99	44	74	8.55	5.15	45
45	5.74	4.41	49	75	21.23	14.25	31
46	5.87	4.24	43	76	20.79	10.56	22
47	4.79	3.77	50	78	3.84	2.99	45
48	6.06	3.49	48	79	3.02	2.41	42
49	6.84	4.76	46	81	20.14	11.43	39

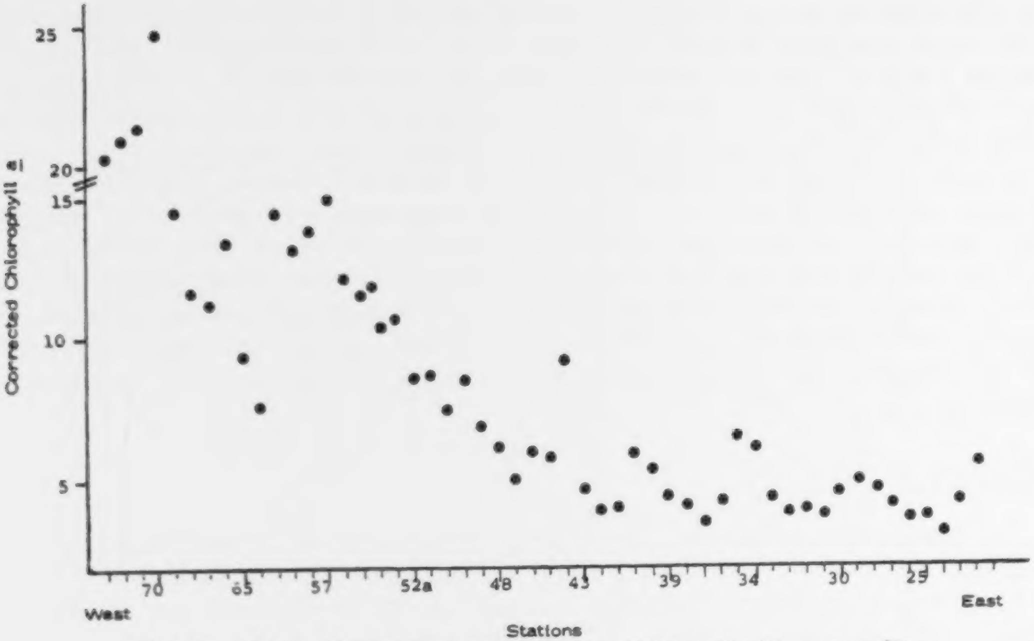


Figure 61. Average corrected chlorophyll a (µg/l) by station, 1973-1975.

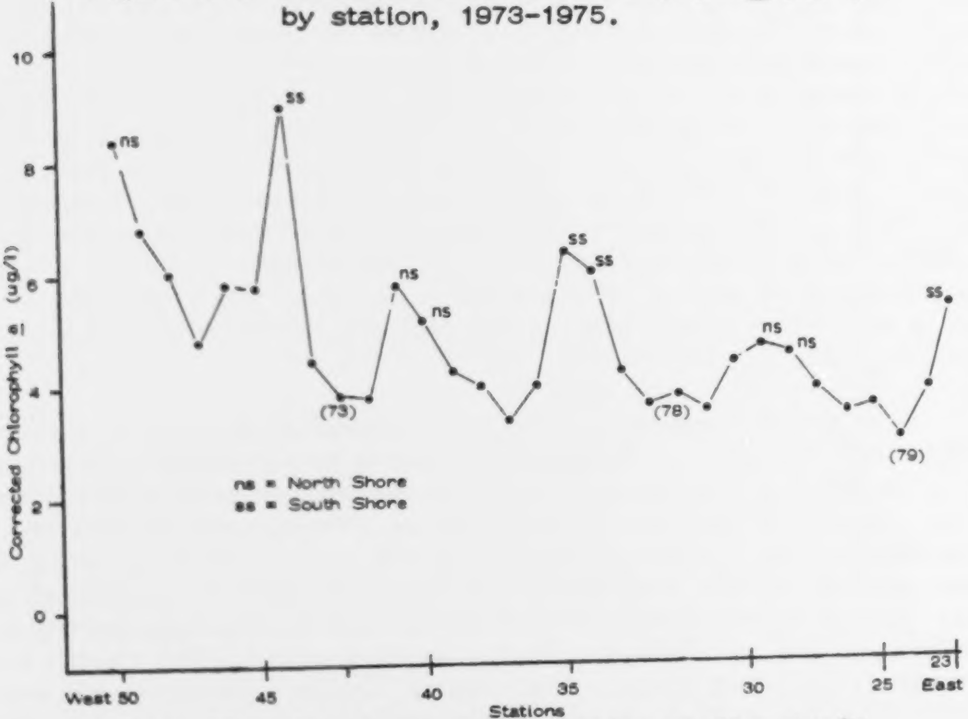


Figure 62. Average corrected chlorophyll a (µg/l) at central basin stations, 1973-1975.

The three-year average chlorophyll a concentrations for each station in the central basin showed a shore versus mid-lake effect (Figure 63). For each transect across the lake, i.e. stations 23 to 29, the south shore (Station 23) exhibited the highest concentrations with a mid-lake low (Station 25) and higher concentrations on the north shore (Station 29). The south shore concentrations were higher than the north shore concentrations with the shore stations in the western central basin having higher concentrations than those in the eastern central basin. Regression analysis showed the basin subdivisions to be of first order significance, accounting for the major variability in the three years of data. The chlorophyll data indicated that areas designated as sub-basins were signficantly different and represented areas reflecting "real" differences in standing crop. These differences demonstrate the need for a synoptic lake survey.

Seasonal Trends

Seasonal variations of chlorophyll a concentrations have been documented by previous studies on the Great Lakes. Although each of the Lake Erie sub-basins exhibited somewhat different seasonal trends, two major effects were evident. The mid-lake central basin and to a lesser extent the north and south shoreline exhibited an early spring maximum, a summer minimum and a rapid increase following fall turnover. The western basin and Sandusky sub-basin both had highest average concentrations during the summer months and lower concentrations in both spring and fall. The percent of the yearly total chlorophyll a and pheopigment present during each cruise substantiates these western and central basin trends (Tables 54 and 55). Contour maps of corrected chlorophyll a concentrations averaged for all depths from each cruise of 1973 through 1975 further depict seasonal trends (Figures 64-78). Volume-weighted cruise tonnages and concentrations of corrected chlorophyll a and pheopigment a are presented for the central (Table 56) and western (Table 57) basins.

The factors responsible for the seasonal responses of the phytoplankton are complex. Seasonal variations in temperature and light are of primary significance in the development of phytoplankton standing crop. As the vernal equinox approaches, the sun moves directly overhead resulting in a greater percent of the sun's light penetrating the water column. This provides more available light for photosynthesis while increasing the water temperature. During the late spring and summer months low turbidity in the western and central basins further enhances light penetration. The shallow western basin warms more rapidly than the deeper central basin and maintains a higher temperature throughout the summer. These conditions plus the availability of nutrients

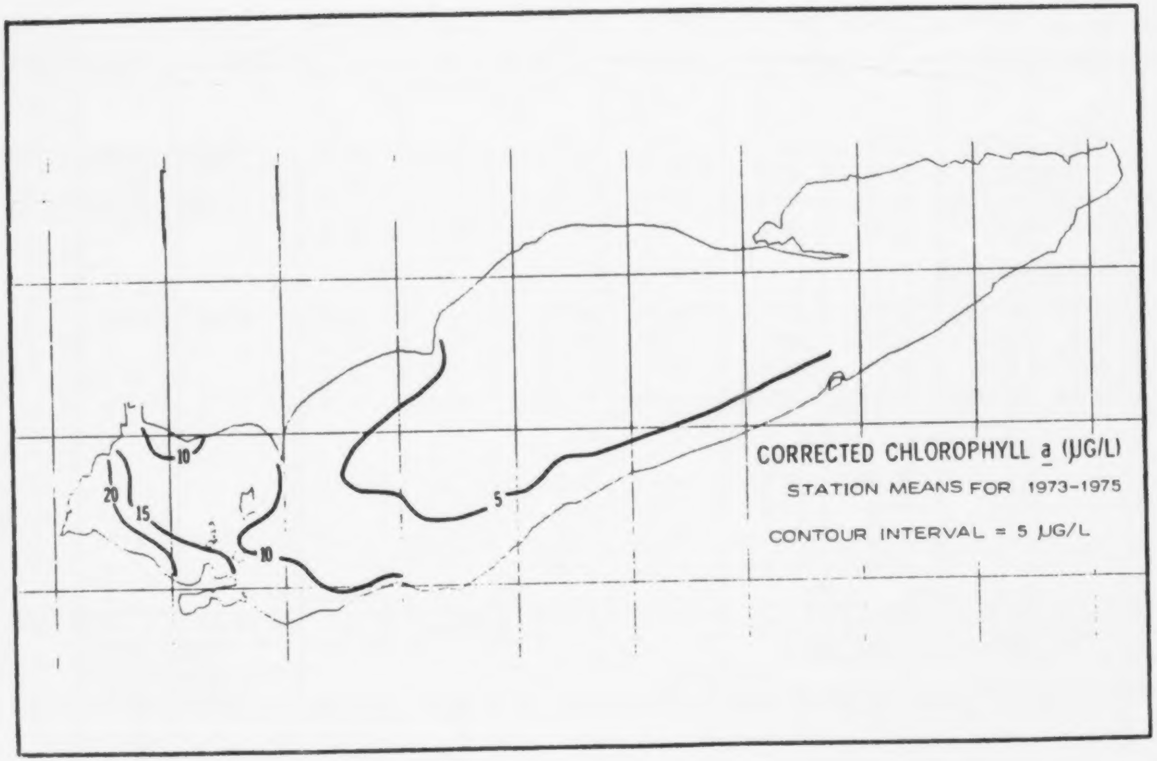

CORRECTED CHLOROPHYLL a (ΜG/L)
STATION MEANS FOR 1973-1975
CONTOUR INTERVAL = 5 ΜG/L
5
10
10
15
20

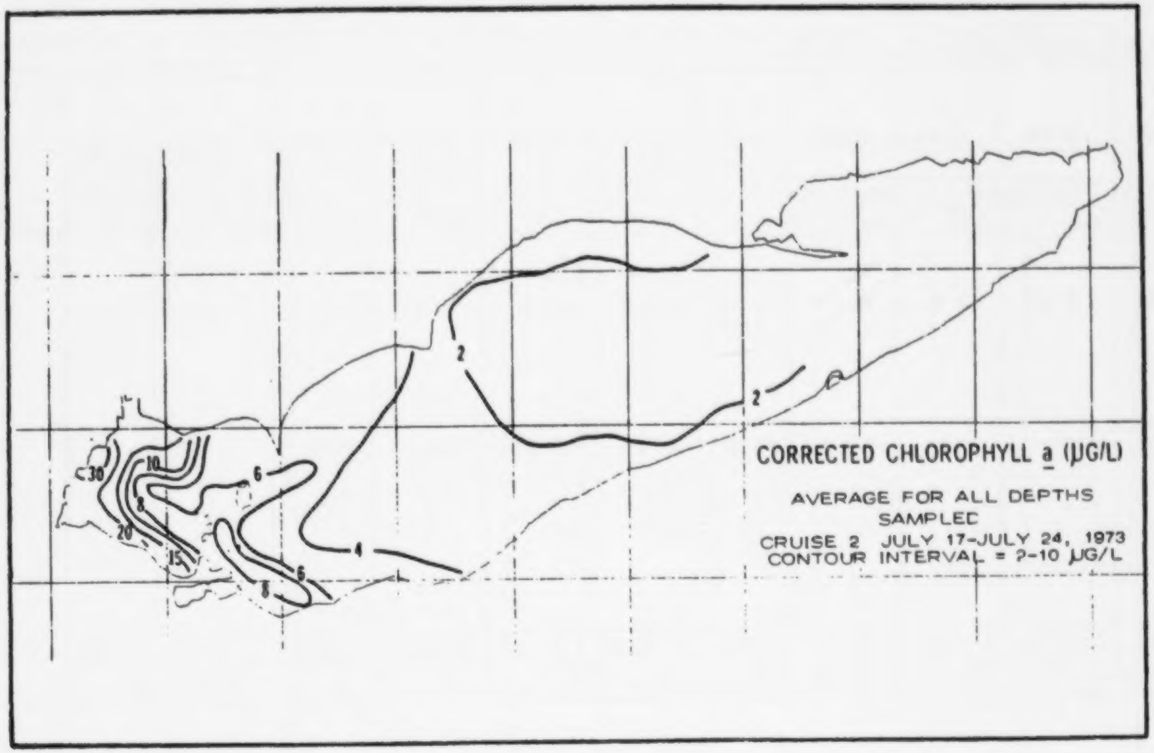
Figure 63. Corrected chlorophyll a (μg/l) station means for 1973-1975.

TABLE 54. PERCENT OF ANNUAL TOTAL CORRECTED CHLOROPHYLL a AND PHEOPIGMENT a CONTRIBUTED AT EACH CRUISE INTERVAL - CENTRAL BASIN

		Unstratified		Stratified								Unstratified	
		April-May		June		July		Aug- Sept		Sept-Oct		Oct-Dec	
Year	Limnion	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a
1973	epi					12.6	19.8	20.8	24.1				
	meso					1.5	2.3	1.8	3.6				
	hypo					3.6	3.3	3.0	3.8				
	total					17.7	25.4	25.6	31.5			56.7	43.1
1974	epi			5.9	4.3	8.2	9.4	12.6	10.1	13.3	23.9		
	meso			0.7	0.6	0.2	0.4	0.9	0.9	0.5	0.9		
	hypo			3.0	3.6	1.2	2.7	1.6	3.5	1.1	2.7		
	total	13.9	13.0	9.6	8.5	9.6	12.5	15.1	14.5	14.9	27.5	36.8	23.6
1975	epi			3.6	3.0	4.4	2.2	17.3	9.5				
	meso			0.7	0.7	1.1	0.6	1.0	0.7				
	hypo			3.3	3.0	3.2	1.9	3.5	3.0				
	total	14.4	26.4	7.6	6.7	8.7	4.7	21.8	13.2	28.2	13.3	19.2	35.7

TABLE 55. PERCENT OF ANNUAL TOTAL CORRECTED CHLOROPHYLL a AND PHEOPIGMENT a CONTRIBUTED AT EACH CRUISE INTERVAL - WESTERN BASIN

Year	Limnion	April-May		June		July		Aug-Sept		Sept-Oct		Oct-Dec	
		Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a
1973													
	epi												
	meso												
	hypo												
	total					26.7	43.6	37.2	25.1			36.1	31.3
1974													
	epi												
	meso												
	hypo												
	total	11.1	8.0	12.7	10.7	20.8	24.8	21.2	22.6	16.6	24.2	17.5	9.8
1975													
	epi												
	meso												
	hypo												
	total	12.7	18.3	25.8	16.6	21.4	11.6	19.8	18.8	14.8	20.5	5.5	14.1



CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS SAMPLEC
CRUISE 2 JULY 17-JULY 24, 1973
CONTOUR INTERVAL = 2-10 µG/L
2
2
2
4
6
6
8
8
10
15
20
30

Figure 64. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 2, July 17-July 24, 1973.

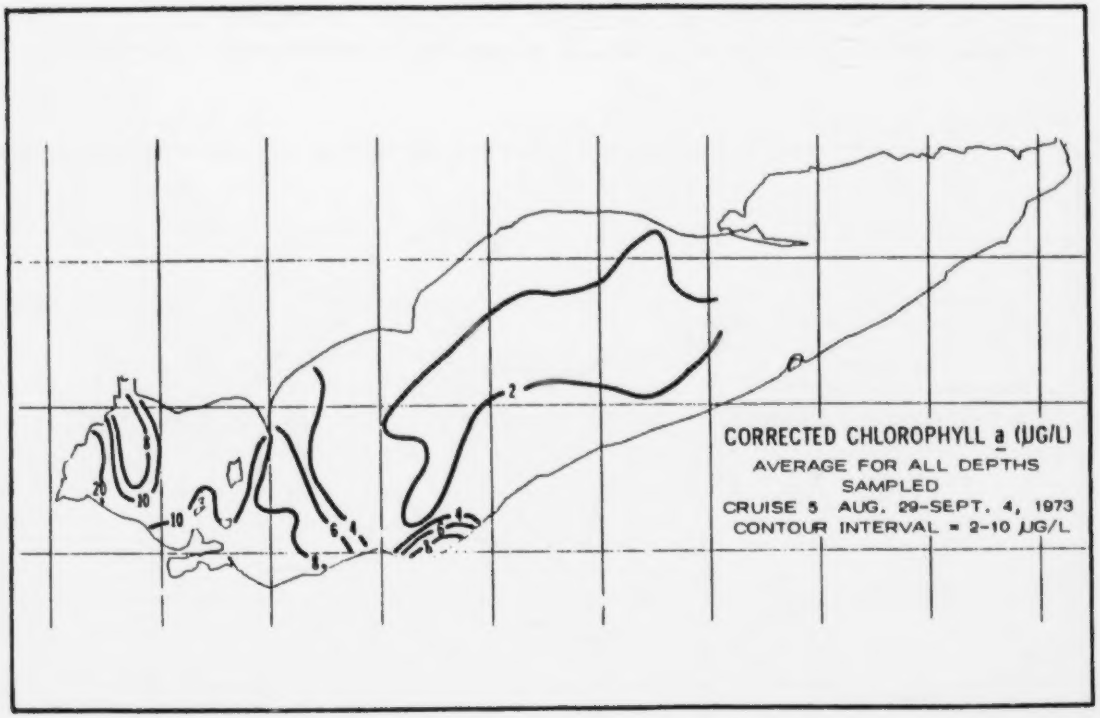

CORRECTED CHLOROPHYLL a (UG/L)
AVERAGE FOR ALL DEPTHS SAMPLED
CRUISE 5 AUG. 29-SEPT. 4, 1973
CONTOUR INTERVAL = 2-10 UG/L
20
8
10
10
6
4
8
2
4
6

Figure 65. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 5, August 29-September 4, 1973.

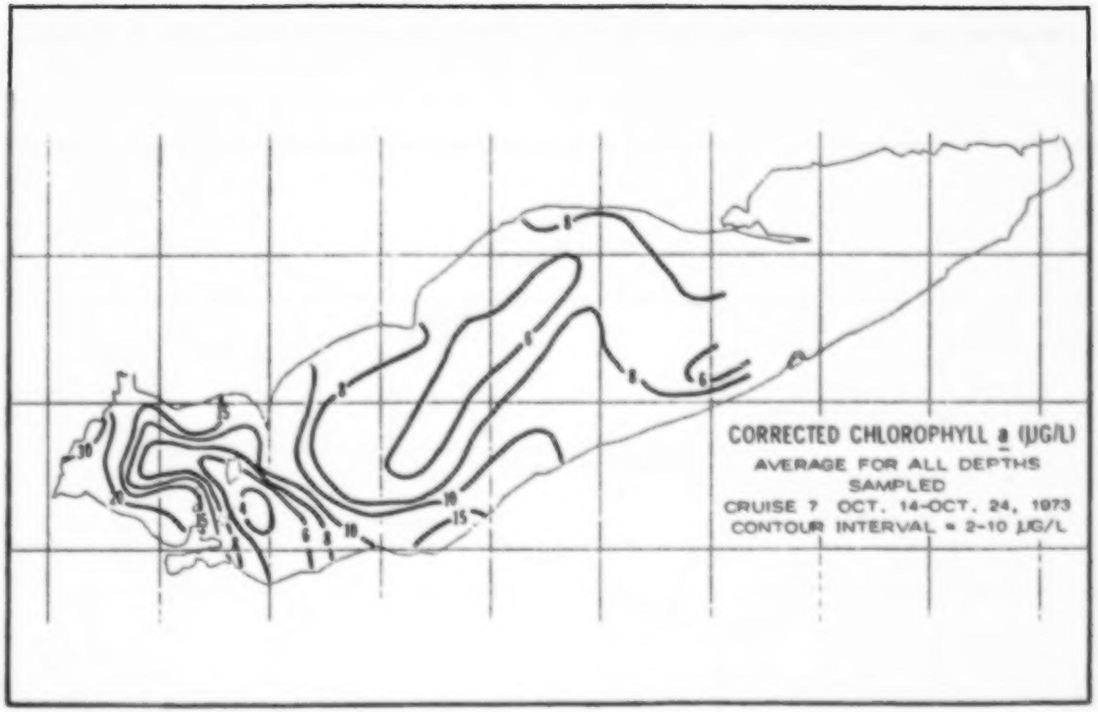

CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS
SAMPLED
CRUISE 7 OCT. 14-OCT. 24, 1973
CONTOUR INTERVAL = 2-10 µG/L
30
20
15
10
8
6
15
10
8
6

Figure 66. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 7, October 14-October 24, 1973.

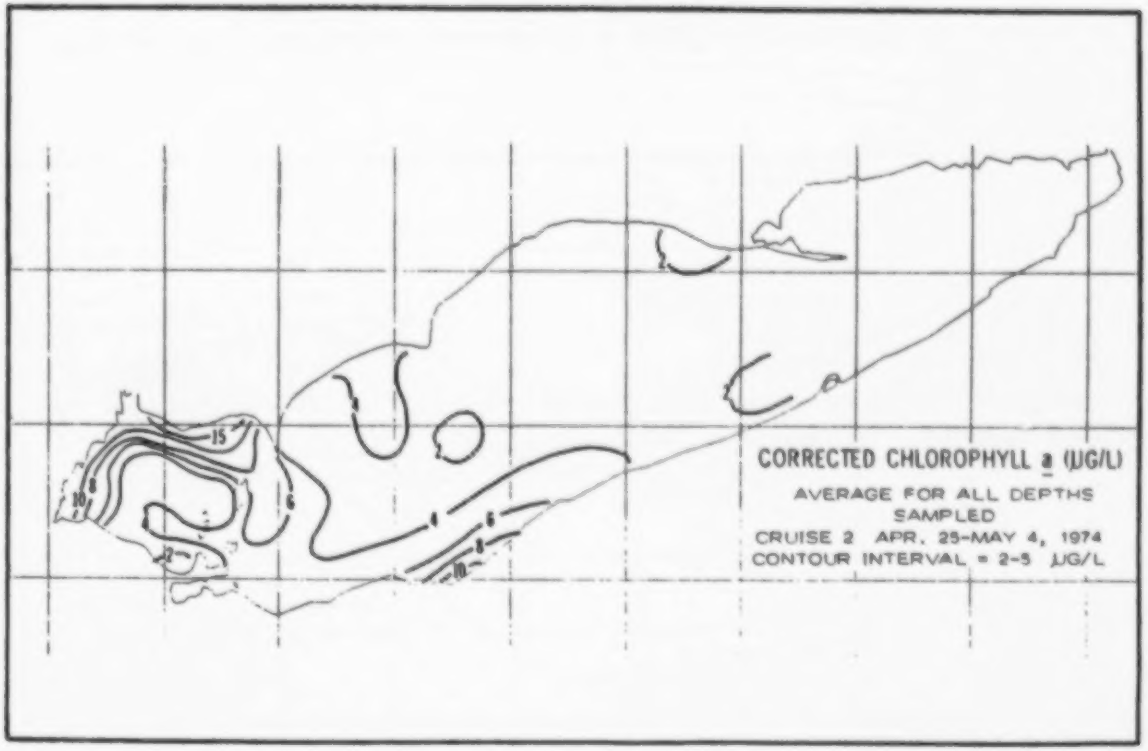
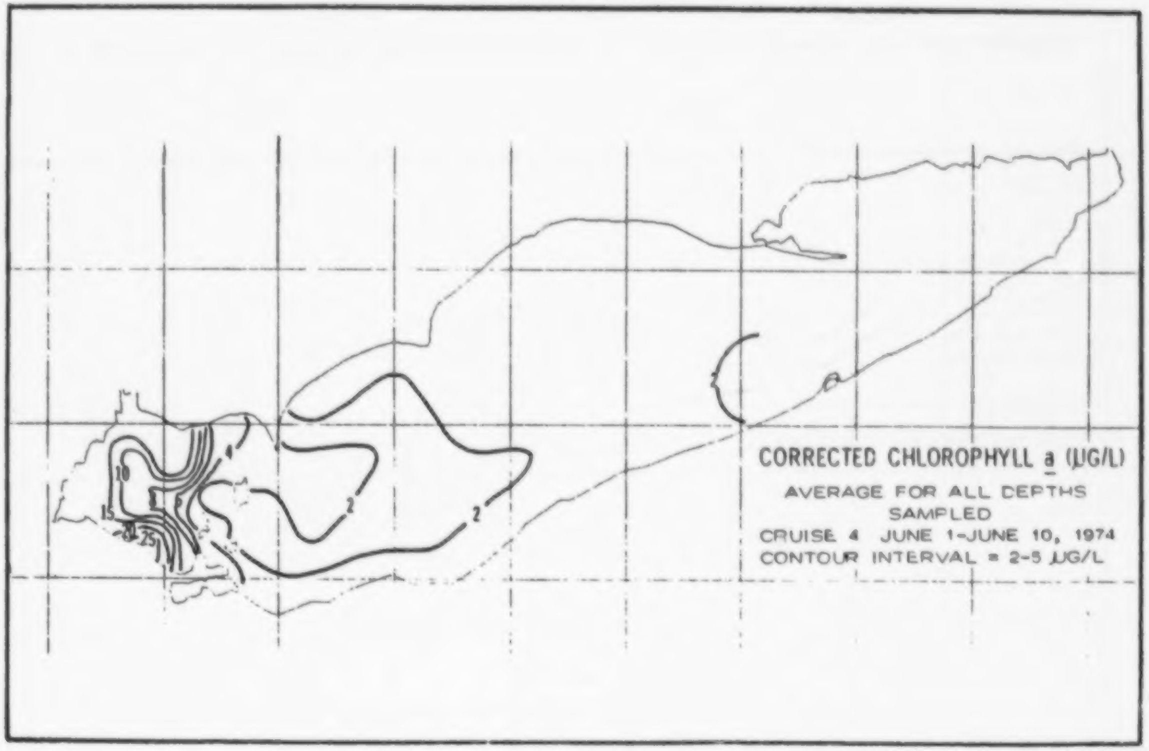

CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS SAMPLED
CRUISE 2 APR. 25-MAY 4, 1974
CONTOUR INTERVAL = 2-5 µG/L
15
10
8
6
12
4
6
8
10

Figure 67. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 2, April 25-May 4, 1974.



CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS
SAMPLED
CRUISE 4 JUNE 1-JUNE 10, 1974
CONTOUR INTERVAL = 2-5 µG/L
10
15
20
25
4
2
2

Figure 68. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 4, June 1-June 10, 1974.

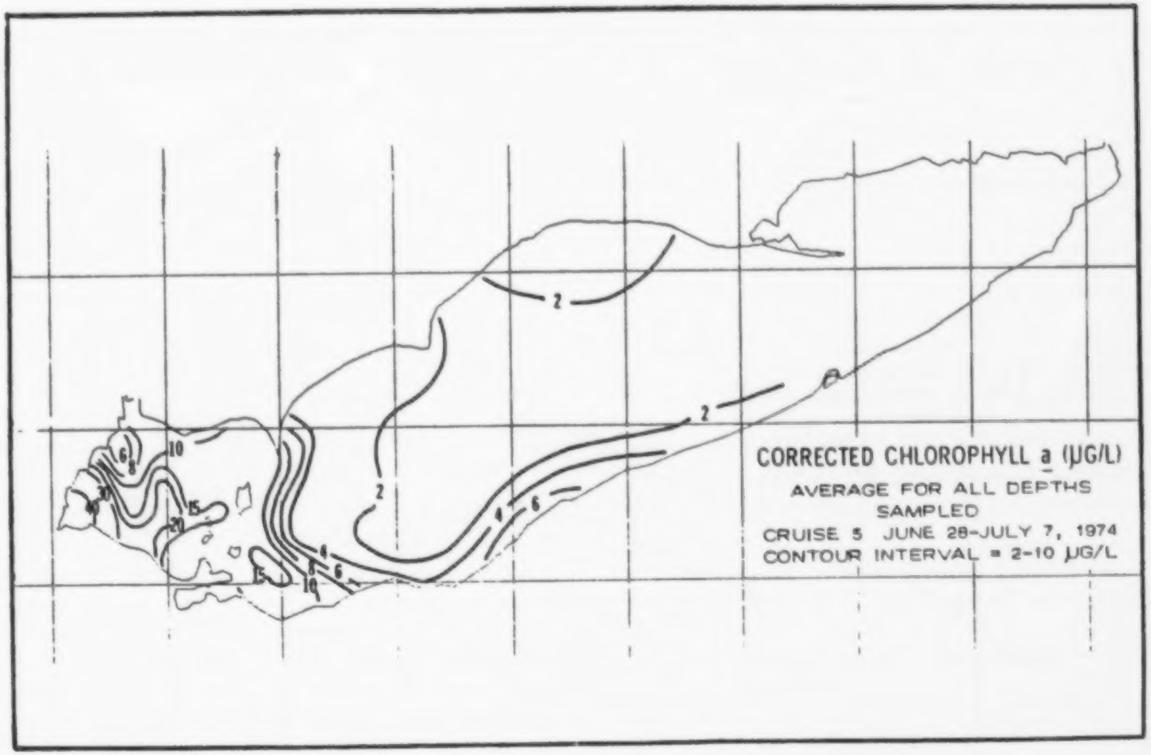

CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS SAMPLED
CRUISE 5 JUNE 28-JULY 7, 1974
CONTOUR INTERVAL = 2-10 µG/L
2
2
2
4
6
4
6
8
10
15
10
15
20
30
40
6
8

Figure 69. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 5, June 28-July 7, 1974.

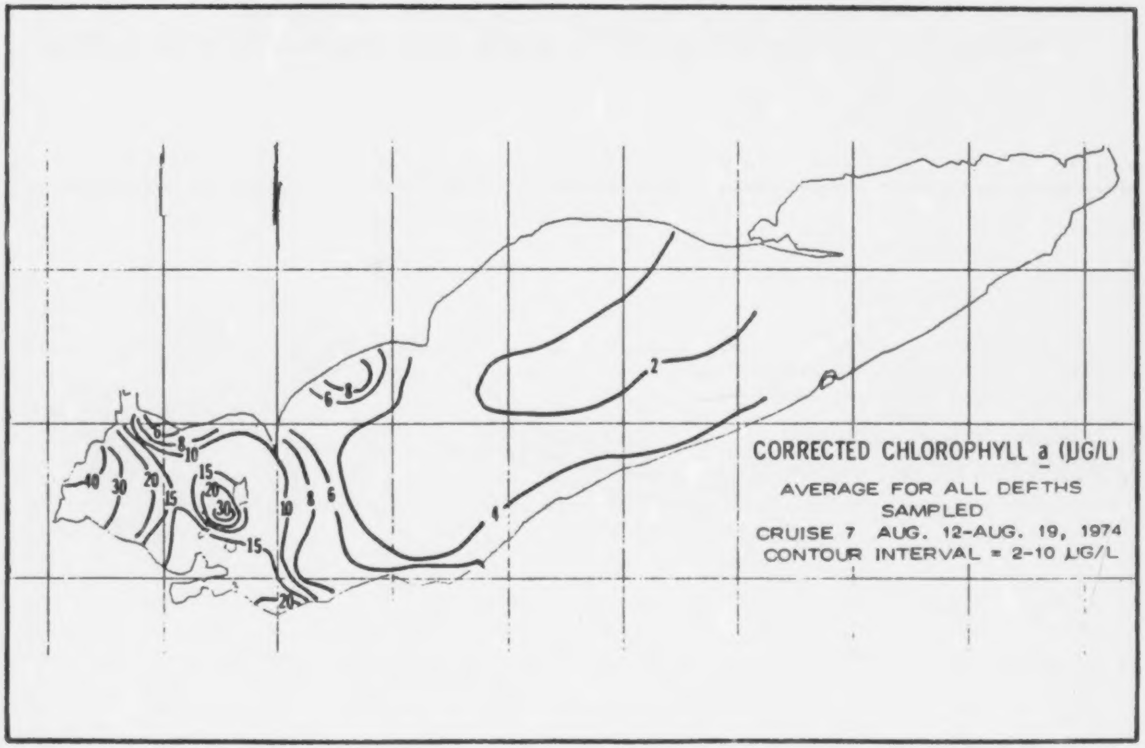

CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEFTHS
SAMPLED
CRUISE 7 AUG. 12-AUG. 19, 1974
CONTOUR INTERVAL = 2-10 µG/L
40
30
20
15
6
8
10
15
20
30
15
20
10
8
6
6
8
4
2

Figure 70. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 7, August 12-August 19, 1974.

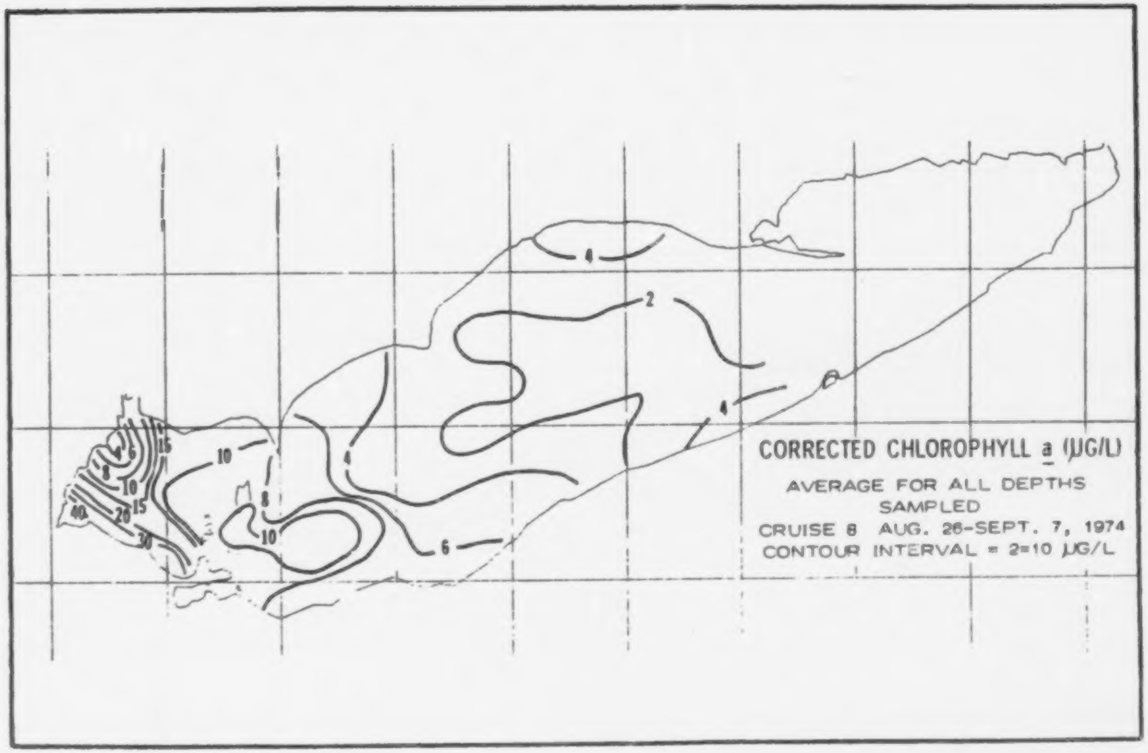

CORRECTED CHLOROPHYLL a (μG/L)
AVERAGE FOR ALL DEPTHS SAMPLED
CRUISE 8 AUG. 26-SEPT. 7, 1974
CONTOUR INTERVAL = 2=10 μG/L
4
2
4
4
6
8
10
10
15
10
8
6
4
10
15
20
30
40

Figure 71. Corrected chlorophyll a (μg/l) average for all depths sampled, cruise 8, August 26-September 7, 1974.

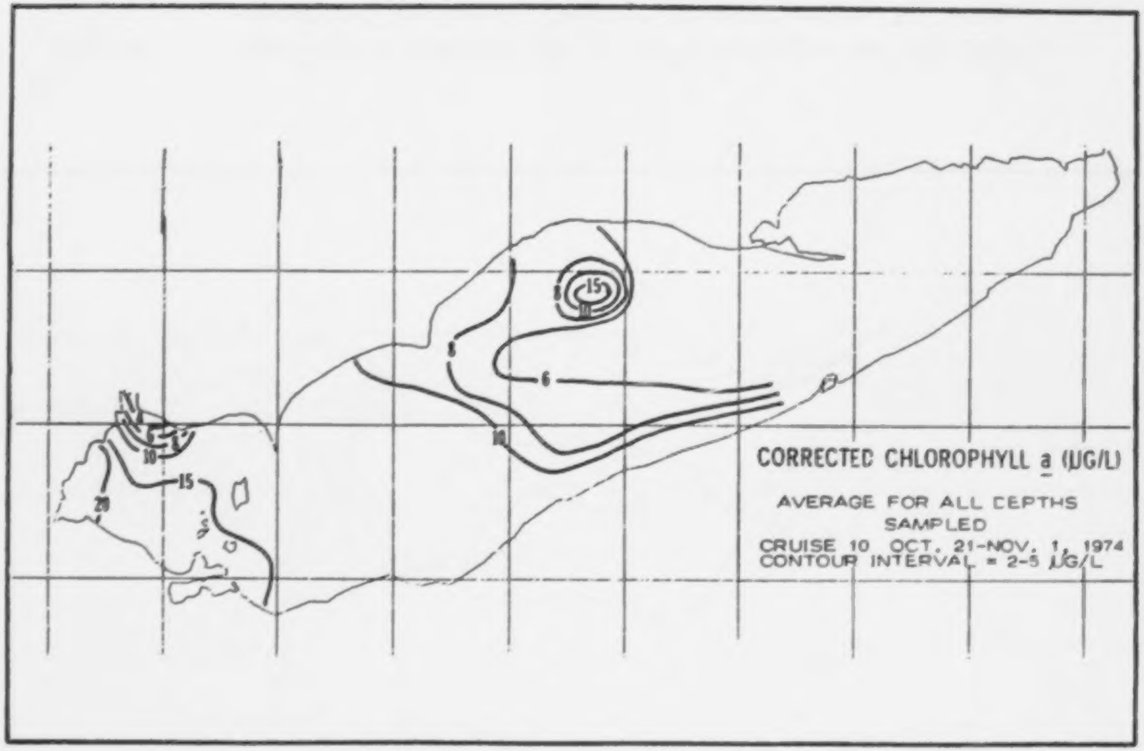

CORRECTED CHLOROPHYLL a (µG/L)
AVERAGE FOR ALL DEPTHS SAMPLED
CRUISE 10 OCT. 21-NOV. 1, 1974
CONTOUR INTERVAL = 2-5 µG/L
15
10
8
6
10
20
15
10
8

Figure 72. Corrected chlorophyll a (µg/l) average for all depths sampled, cruise 10, October 21-November 1, 1974.

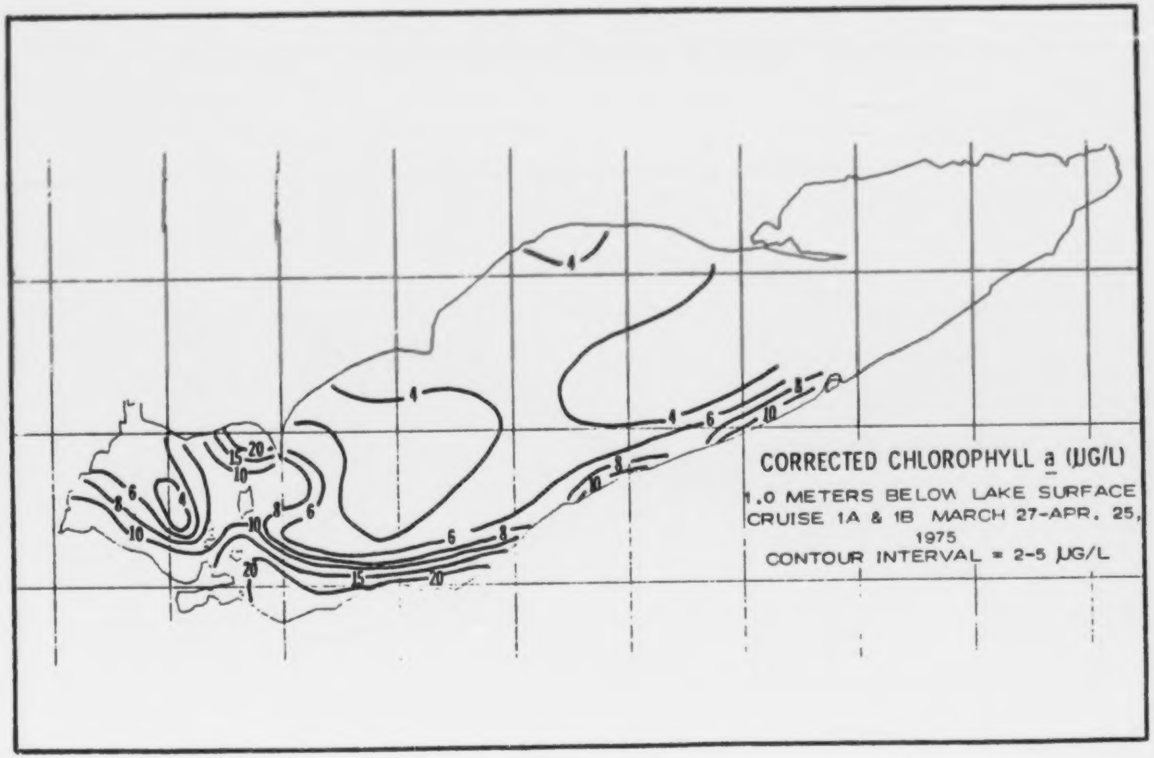
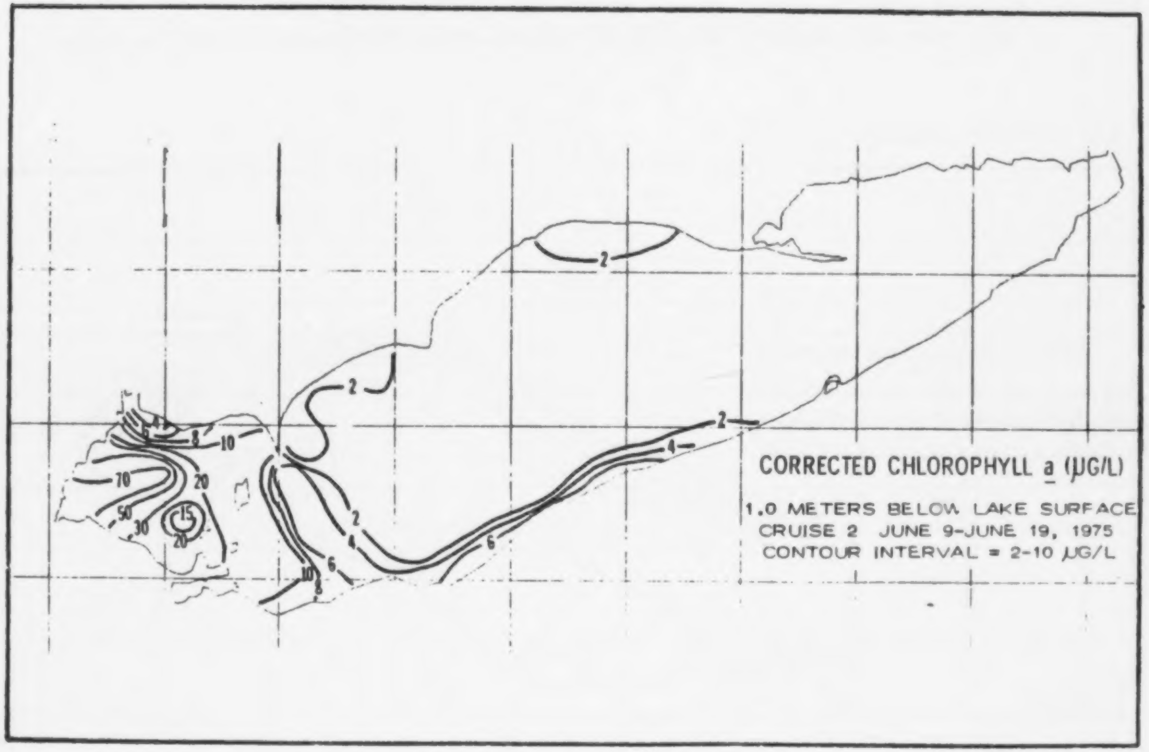

CORRECTED CHLOROPHYLL a (µG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 1A & 1B MARCH 27-APR. 25, 1975
CONTOUR INTERVAL = 2-5 µG/L
4
6
8
10
15
20

Figure 73. Corrected chlorophyll a (µg/l), cruise 1A and 1B, March 27-April 25, 1975.



CORRECTED CHLOROPHYLL a (µG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 2 JUNE 9-JUNE 19, 1975
CONTOUR INTERVAL = 2-10 µG/L
2
2
2
2
4
4
6
6
8
8
10
10
10
20
20
30
50
70
15

Figure 74. Corrected chlorophyll a (µg/l), cruise 2, June 9-June 19, 1975.

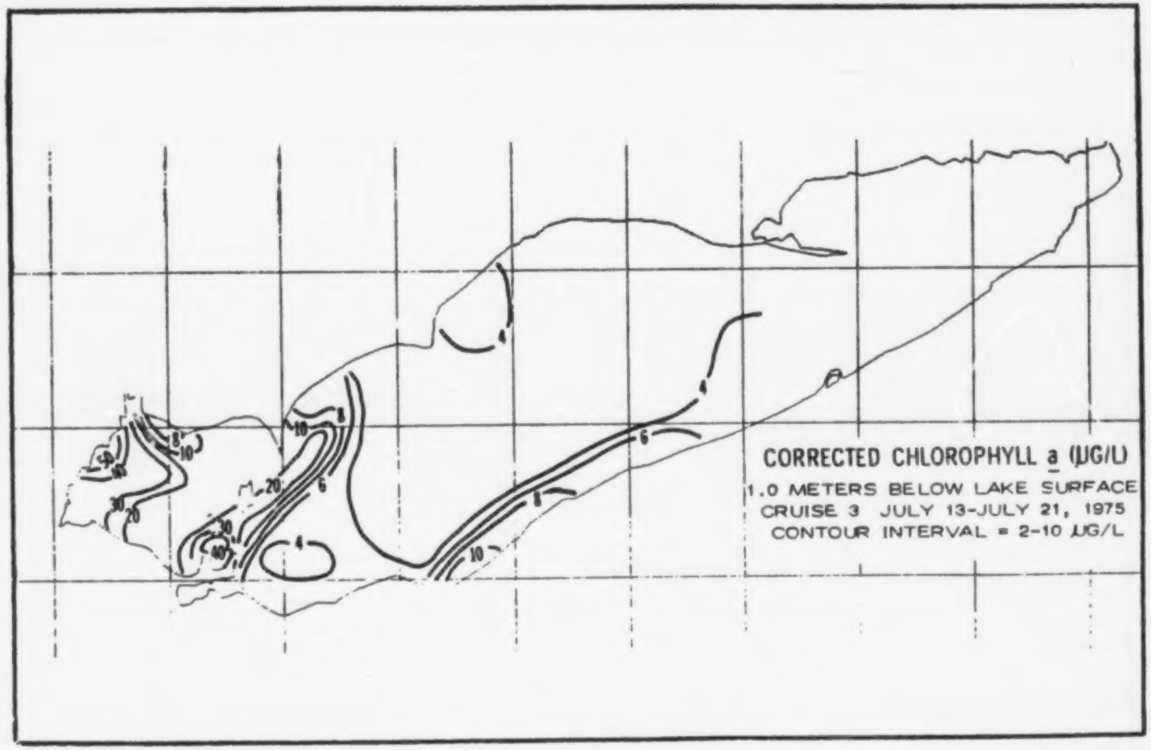

CORRECTED CHLOROPHYLL a (µG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 3 JULY 13-JULY 21, 1975
CONTOUR INTERVAL = 2-10 µG/L
4
6
8
10
20
30
40
50

Figure 75. Corrected chlorophyll a (µg/l), cruise 3, July 13-July 21, 1975.

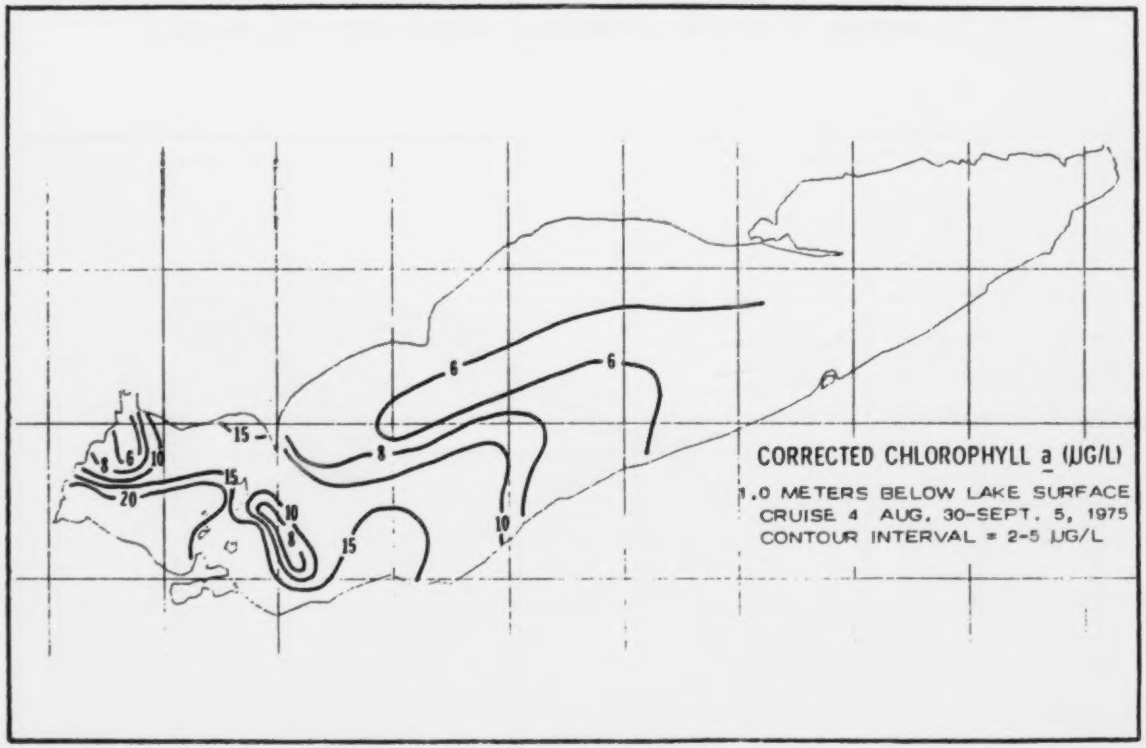

CORRECTED CHLOROPHYLL a (μG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 4 AUG. 30-SEPT. 5, 1975
CONTOUR INTERVAL = 2-5 μG/L
6
6
8
10
15
15
10
8
15
20
8
6
10
15
10

Figure 76. Corrected chlorophyll a (μg/l), cruise 4, August 30-September 5, 1975.

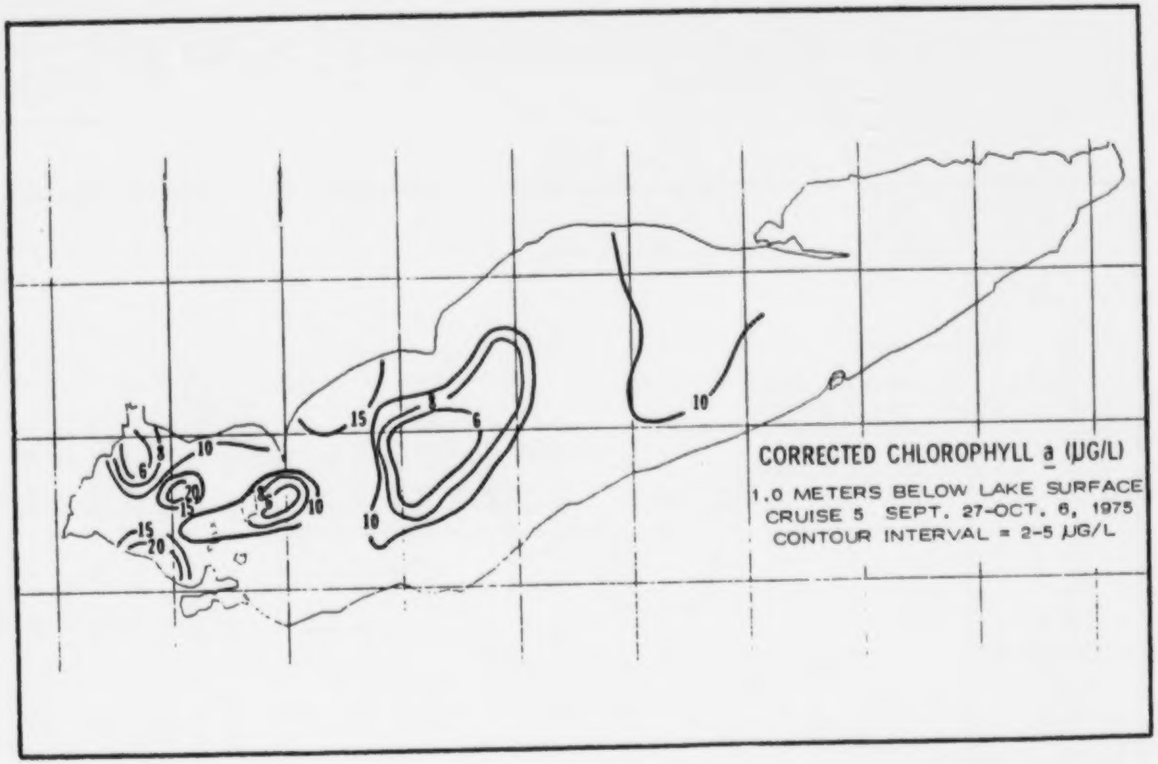

CORRECTED CHLOROPHYLL a (µG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 5 SEPT. 27-OCT. 6, 1975
CONTOUR INTERVAL = 2-5 µG/L
10
15
8
6
10
20
15
15
20
8
5
10
10
10

Figure 77. Corrected chlorophyll a (µg/l), cruise 5, September 27-October 6, 1975.

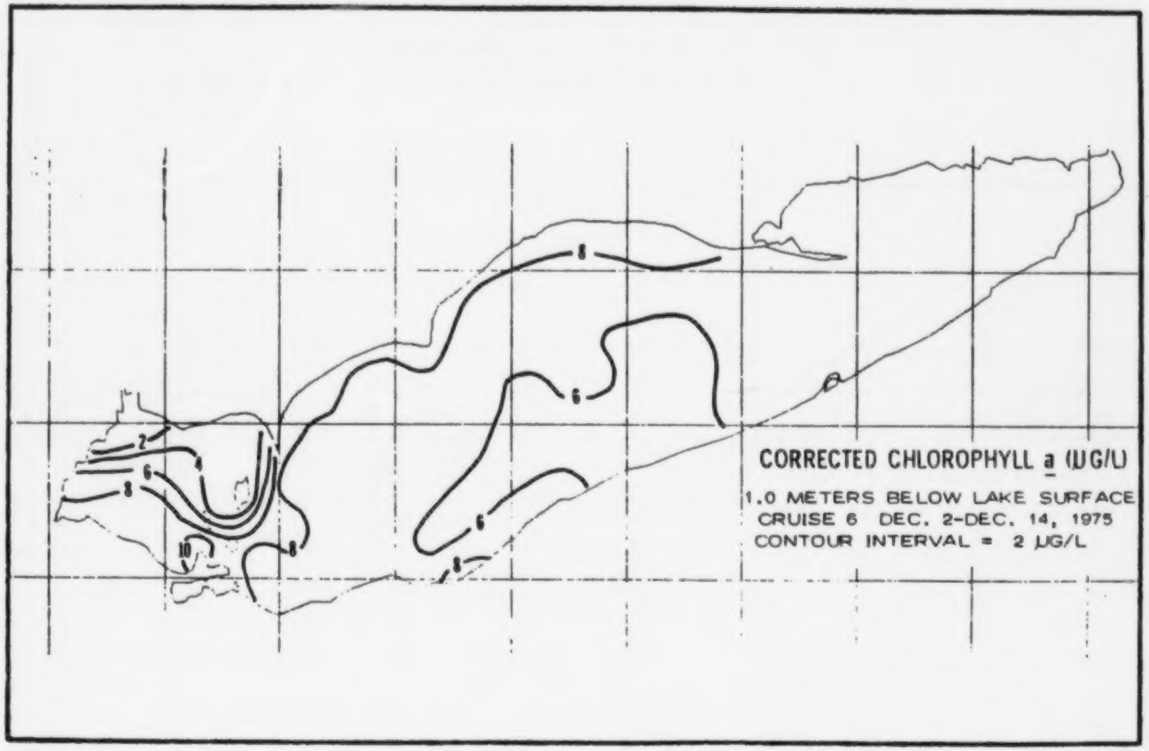

8
6
2
6
4
8
10
8
6
8
CORRECTED CHLOROPHYLL a (UG/L)
1.0 METERS BELOW LAKE SURFACE
CRUISE 6 DEC. 2-DEC. 14, 1975
CONTOUR INTERVAL = 2 UG/L

Figure 78. Corrected chlorophyll a (µg/l), cruise 6, December 2-December 14, 1975.

TABLE 56. CORRECTED CHLOROPHYLL a AND PHEOPIGMENT a - CENTRAL BASIN

	Unstratified		Stratified			
	April-May		June		July	
Limnion	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a
1973						
Epi tons					535.18	248.53
μg/l					2.34	1.08
Meso tons					63.97	28.90
μg/l					2.86	1.29
Hypo tons					152.21	41.21
μg/l					2.48	0.67
Total tons					751.36	318.64
μg/l					2.40	1.02
1974						
Epi tons	1082.73	231.82	458.06	78.05	641.82	168.82
μg/l	3.47	0.79	2.34	0.40	2.58	0.68
Meso tons			58.29	11.05	18.28	6.34
μg/l			2.56	0.49	1.46	0.51
Hypo tons			233.22	65.54	92.21	48.73
μg/l			2.49	0.70	1.84	0.79
Total tons			749.57	154.64	752.31	223.89
μg/l			2.40	0.50	2.41	0.72
1975						
Epi tons	1571.02	584.20	395.11	66.90	482.69	49.08
μg/l	5.09	1.89	2.27	0.38	2.64	0.27
Meso tons			81.48	14.78	121.26	13.96
μg/l			2.65	0.48	3.41	0.39
Hypo tons			362.84	67.18	351.75	41.41
μg/l			3.47	0.64	3.89	0.46
Total tons			839.43	148.86	955.70	104.45
μg/l			2.71	0.48	3.10	0.34

(continued)

TABLE 56 (continued)

	Stratified		Unstratified			
	Aug-Sept		Sept-Oct		Oct-Dec	
Limnion	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a
1973						
Epi tons	884.99	302.90			2409.12	541.78
µg/l	3.72	1.27			7.87	1.77
Meso tons	75.90	45.64				
µg/l	3.05	1.84				
Hypo tons	129.40	48.07				
µg/l	2.75	1.02				
Total tons	1090.29	389.61				
µg/l	3.52	1.26				
1974						
Epi tons	985.20	181.01	1036.03	429.46	2871.40	423.44
µg/l	4.19	0.77	4.26	1.77	9.45	1.39
Meso tons	72.81	17.01	41.61	17.05		
µg/l	3.05	0.71	2.38	0.98		
Hypo tons	127.02	63.18	85.16	49.02		
µg/l	2.51	1.25	1.76	1.01		
Total tons	1185.03	261.20	1162.80	495.53		
µg/l	3.82	0.84	3.76	1.60		
1975						
Epi tons	1894.42	210.04	3086.02	293.58	2103.32	790.16
µg/l	8.33	0.92	10.05	0.96	6.92	2.60
Meso tons	108.98	14.80				
µg/l	7.16	0.97				
Hypo tons	380.98	66.06				
µg/l	5.77	1.00				
Total tons	2384.38	290.90				
µg/l	7.72	0.94				

TABLE 57. CORRECTED CHLOROPHYLL a AND PHEOPIGMENT a - WESTERN BASIN, 1973-1975

	Chl a	Pheo a	Chl a	Pheo a	Chl a	Pheo a
Limnion	April-May		June		July	
1973						
Epi tons					199.28	141.82
µg/l					8.34	5.93
Meso						
Hypo						
Total						
1974						
Epi tons	210.00	26.17	241.74	34.81	395.09	80.78
µg/l	8.75	1.09	10.03	1.44	16.50	3.37
Meso						
Hypo						
Total						
1975						
Epi tons	244.52	66.01	495.14	60.36	410.76	42.19
µg/l	10.34	2.79	21.07	2.57	17.59	1.81
Meso						
Hypo						
Total						
	Aug-Sept		Sept-Oct		Oct-Dec	
1973						
Epi tons	277.61	81.74			269.37	101.77
µg/l	11.74	3.46			11.99	4.52
Meso						
Hypo						
Total						
1974						
Epi tons	403.22	73.83	316.09	78.60	331.43	31.70
µg/l	17.14	3.14	13.48	3.35	14.65	1.40
Meso						
Hypo						
Total						
1975						
Epi tons	380.86	67.99	284.58	74.21	105.01	51.23
µg/l	16.31	2.91	12.34	3.22	4.66	2.27
Meso						
Hypo						
Total						

in the western basin provide an environment favorable for algal growth, evidenced by the high concentrations of chlorophyll a observed throughout the basin during the summer.

The central basin maintained high chlorophyll a concentrations in the spring prior to stratification and during the fall following turnover. The maximum central basin concentrations were found in the fall just after turnover when the nutrient-rich hypolimnion became mixed with the nutrient-depleted epilimnion. In the late fall, storms cause resuspension of sedimented material, which increases the turbidity. At the same time, water temperatures are decreasing, and, thus, chlorophyll concentrations decline during this period.

Year to Year Trends

In order to facilitate a year to year comparison of chlorophyll a in Lake Erie, volume-weighted quantities (metric tons) were calculated. The cruise by cruise volume-weighted quantities were plotted for 1973 through 1975, and points equidistant between the cruises were used to estimate chlorophyll a values for periods between cruises. The between-cruise estimates and the cruise values were averaged for each year to give estimated chlorophyll a tonnages for the western and central basins. This procedure was used to compensate for irregular sampling intervals and varying number of cruises over the three-year period. For comparative purposes only, the between-cruise estimates of chlorophyll a from June through November of each year were used due to the great variability found in early spring and late fall data.

From 1973 to 1975, the mean tonnage of corrected chlorophyll a increased in the central basin:

Central Basin	
1973	1201.25 tons
1974	1291.78 tons
1975	1795.08 tons

From 1973 to 1975, an increase of 49 percent was estimated and the greatest year to year difference, a 38 percent increase in corrected chlorophyll a, occurred between 1974 and 1975. This large increase was attributed to a greater hypolimnion concentration of chlorophyll a in 1975 than in 1974. The establishment of the thermocline higher in the water column in 1975 resulted in a larger hypolimnion volume. Since a greater portion of the hypolimnion was in the photic zone and nutrients were less likely to become limiting, the hypolimnion was able to support a larger standing crop of phytoplankton during this year. In addition, the extensive anoxic conditions which developed in the hypolimnion in 1973 and 1974 were not encountered in 1975. Lack of extensive anoxia also provided a more favorable hypolimnion environment than was previously observed.

From 1973 to 1975 the mean tonnage of corrected chlorophyll a increased in the western basin, with the greatest increase in mean tons occurring between 1973 and 1974. The three-year data is as follows:

Western Basin	
1973	236.96 tons
1974	342.51 tons
1975	395.01 tons

The corrected chlorophyll a tonnages were estimated to be 44.5 percent greater in 1974 than 1973, and a further increase of 15 percent was calculated for 1975 and 1974.

The significance of year to year differences of chlorophyll a tonnage in Lake Erie is somewhat difficult to evaluate over a short time period. Yearly changes in standing crop can be expected due to seasonal variation, different meteorological effects and cruise scheduling. Only a sampling program spanning several additional years will provide the necessary information to evaluate changes in the trophic status of the lake.

Historical Trends

Few previous studies on Lake Erie have examined chlorophyll concentrations (Table 58). Tucker (1949) utilized 1939 western basin chlorophyll data supplied by Chandler and Weeks and reported a good correlation (r = 0.78) between phytoplankton counts and plankton pigments using the technique developed by Harvey (1934). Brydges (1971) reported western basin and north shore data collected between 1967 and 1969. Spectrophotometric determinations were made on pigments extracted in 90 percent acetone and concentrations were calculated using the equations developed by Richards and Thompson (1952). Brydges found chlorophyll a to be positively correlated with total phosphorus, with the highest concentrations of both chlorophyll a and total phosphorus found in the western portion of the lake. Only two entire Lake Erie chlorophyll surveys have been undertaken, one by the Federal Water Pollution Control Administration (FWPCA, 1968) in May, July and October of 1967 and January and August of 1968, and another by Glooschenko et al. (1974) based on 10 cruises from April to December of 1970.

TABLE 58. SIMILAR STATIONS FROM CHLOROPHYLL SURVEYS UNDERTAKEN BY THE FEDERAL WATER POLLUTION CONTROL AGENCY (1968) AND THE CENTER FOR LAKE ERIE AREA RESEARCH 1974-1975

STATION NUMBERS	
FWPCA, 1967 - 1968	CLEAR, 1974 - 1975
D9-1	81
E2-1	70
G12-1	50
D13-1	51
F16-1	47
H20-1	73
L30-1	78
L36-1	79

The FWPCA sampled 30 stations along a longitudinal transect of the entire lake (Figure 79). Eight FWPCA stations are comparable to CLEAR western and central basin stations (Table 58) and were used for comparison. The original FWPCA data utilized Richards and Thompson's equations (1952), and the data was reported as chlorophylls *a* plus *b*. The raw data absorbencies were obtained and recalculated using the SCOR/UNESCO chlorophyll *a* equation (1966). The averages (surface and mid-depths) for the eight stations on each of the May, July and October cruises were recalculated and plotted (Figure 80). The FWPCA 1967 May to October average chlorophyll *a* was estimated to be 4.86 μg/l. Cruise averages based on the eight similar CLEAR stations during corresponding time periods were plotted (Figure 80). The CLEAR data for 1973 have not been included in this analysis because of missing data prior to July. The yearly SCOR/UNESCO chlorophyll *a* averages for 1974 and 1975 were 9.24 μg/l respectively. The 1974 and 1975 chlorophyll *a* concentrations were higher than the 1967 averages which may be only partially attributed to differences in sampling schedules. There was an increase of 7.08 μg/l of chlorophyll *a* from 1967 to 1975 for the western and central basins representing an increase of 146 percent.

Problems were encountered in utilizing the 1967 FWPCA data. The original FWPCA 645 nm absorbences (chlorophyll *b*) were found to be as high or higher than the absorbences at 663 nm (chlorophyll *a*). Absorbences for chlorophyll *b* should be consistently lower than chlorophyll *a* absorbences. It has been pointed out that the Beckman D spectrophotometer used by the FWPCA may have been miscalibrated (Cornelius Weber, U.S. EPA, Cincinnati, personal communication). Thus, the FWPCA chlorophyll data lost much of its validity.

Glooschenko, Moore and Vollenweider (1974) sampled 5 western basin and 12 central basin stations during 10 cruises in 1970. Samples were collected at 1 m and 5 m depths and integrated. The analytical procedures were similar to those used by CLEAR, 1973 through 1975, making the data comparable. Five western basin and twelve central basin CLEAR stations similar in location to Glooschenko were selected for comparison (Figure 81 and Table 59). Basin averages were calculated using only surface and mid-depth or lower epilimnion values for comparison with the 1970 study. Only SCOR/UNESCO chlorophyll *a* values were compared since the 1970 report did not include corrected chlorophyll *a*. Yearly averages were calculated for 1970 and 1973 through 1975 based on cruises from June to November (Tables 60 and 61).

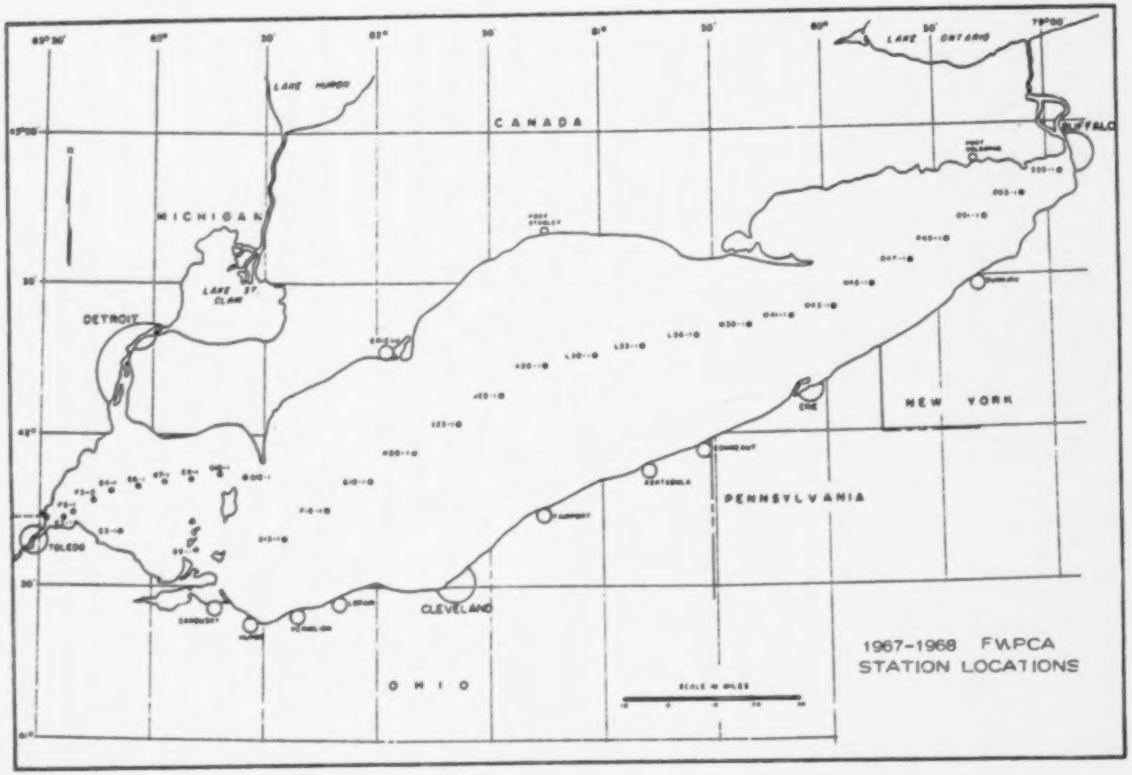

LAKE HURON
LAKE ONTARIO
CANADA
MICHIGAN
LAKE ST. CLAIR
DETROIT
TOLEDO
CLEVELAND
ERIE
BUFFALO
NEW YORK
PENNSYLVANIA
OHIO
1967-1968 FWPCA
STATION LOCATIONS
SCALE IN MILES
79°00'
80°
81°
82°
83°30'
42°
30'
41°

Figure 79. FWPCA station locations, 1967-1968.

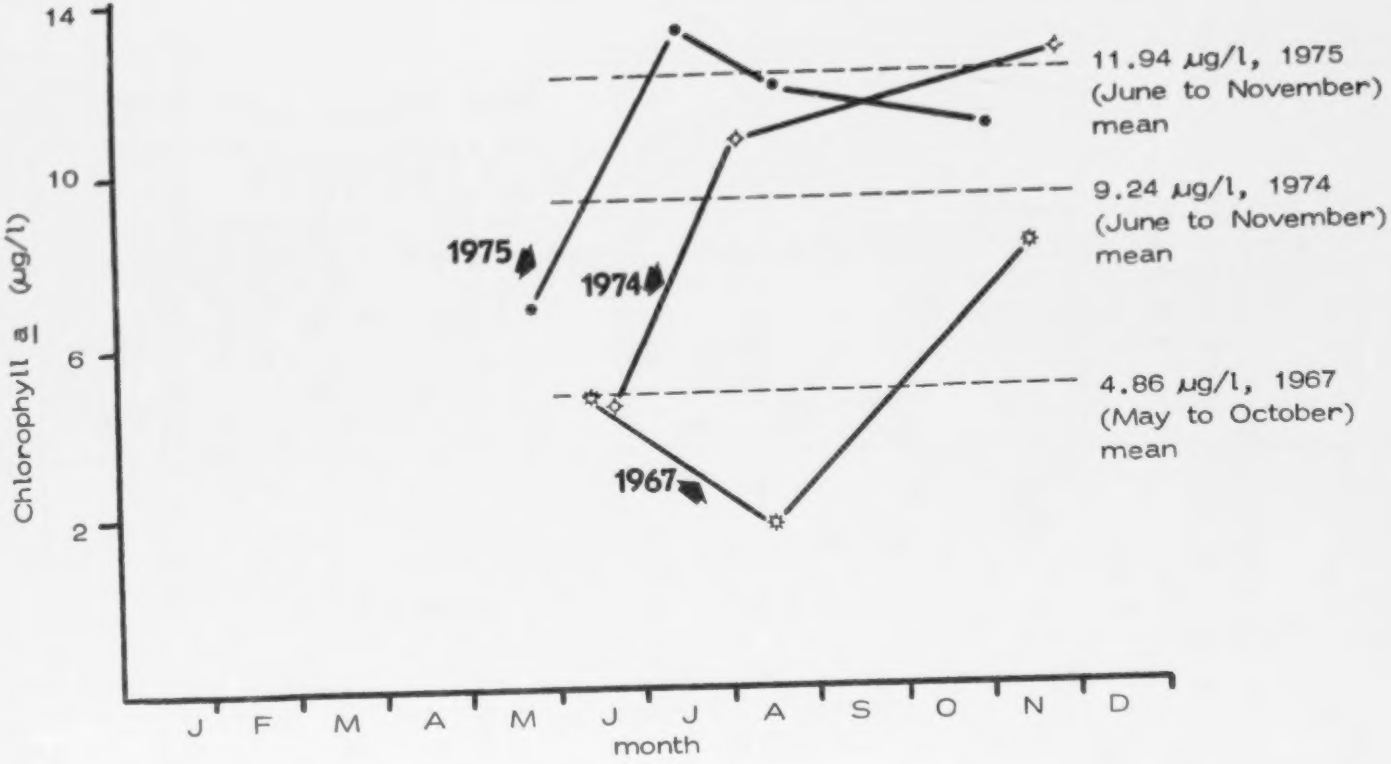


Figure 80. Comparison of central and western basin chlorophyll a values (average of surface and mid-depth values) from the FWPCA, 1967 data and corresponding 1974 and 1975 data.

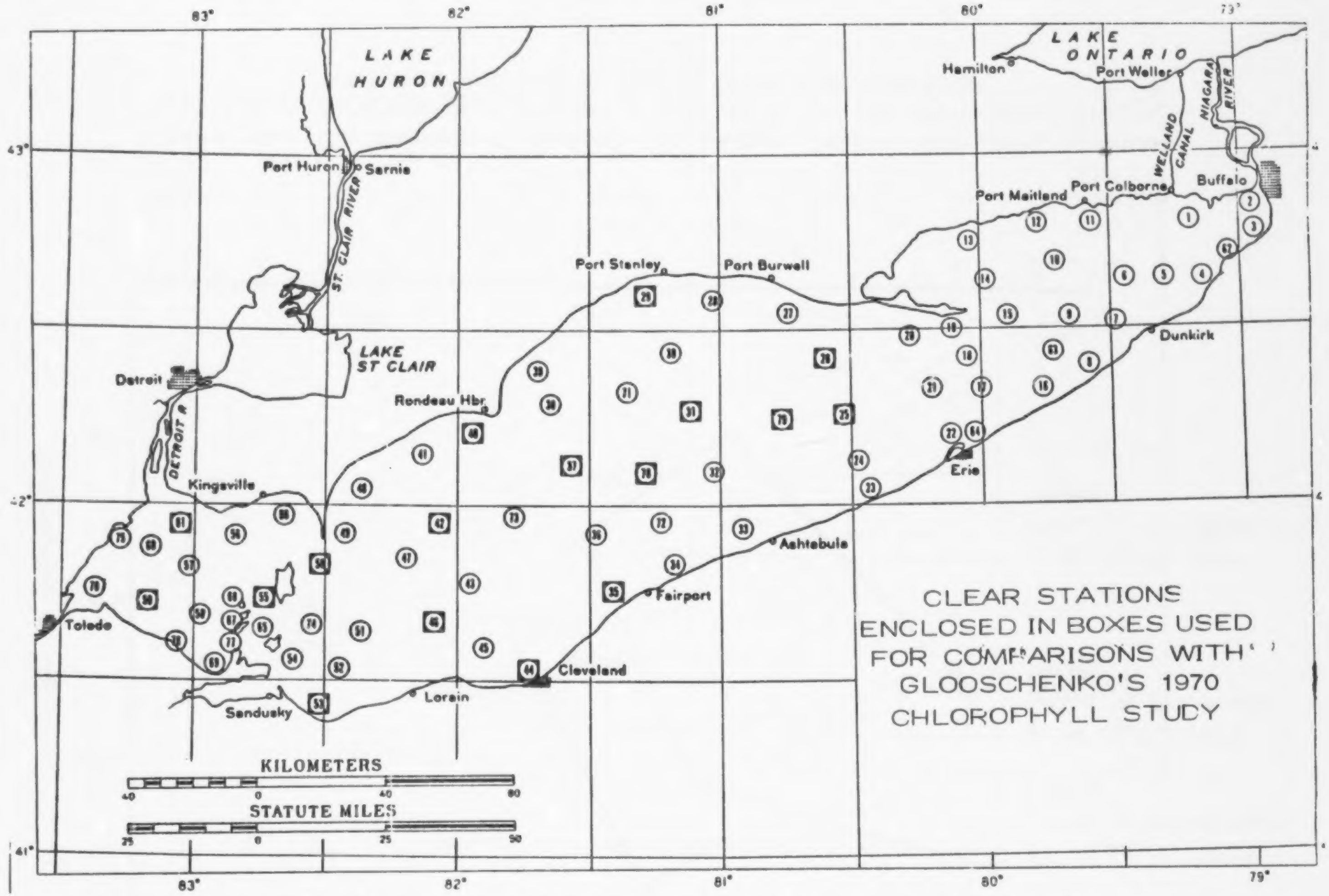

83°
82°
81°
80°
79°
43°
42°
41°
LAKE HURON
LAKE ONTARIO
LAKE ST CLAIR
Hamilton
Port Weller
WELLAND CANAL
NIAGARA RIVER
Buffalo
Port Maitland
Port Colborne
Dunkirk
Erie
Port Huron
Sarnia
ST. CLAIR RIVER
Detroit
DETROIT R.
Port Stanley
Port Burwell
Rondeau Hbr.
Kingsville
Toledo
Sandusky
Lorain
Cleveland
Fairport
Ashtabula
KILOMETERS
40
0
40
80
STATUTE MILES
25
0
25
50
CLEAR STATIONS
ENCLOSED IN BOXES USED
FOR COMPARISONS WITH
GLOOSCHENKO'S 1970
CHLOROPHYLL STUDY

Figure 81. CLEAR stations enclosed in boxes used for comparisons with Glooschenko's 1970 chlorophyll study.

TABLE 59. SIMILAR STATIONS FROM CHLOROPHYLL SURVEYS IN GLOOSCHENKO (1970) AND CLEAR (1973-1975)

Glooschenko, 1970 Station Number	CLEAR, 1973 - 1975 Station Number
Western Basin	Western Basin
23	50
25	61
27	59
29	55
31	53
Central Basin	Central Basin
7	79
9	31
14	37
18	44
22	46
34	40
35	42
37	35
38	78
41	29
44	26
47	25

TABLE 60. AVERAGE CHLOROPHYLL a (μg/l) IN LAKE ERIE 1970 BY MONTH AND WESTERN TO CENTRAL BASIN RATIOS

Cruise	Western	Central	W : C
April 7 - 11	5.9	5.3	1.11 : 1.0
May 6 - 10	4.4	2.9	1.52 : 1.0
June 2 - 6	5.9	2.7	2.19 : 1.0
July 3 - 7	11.9	2.5	4.76 : 1.0
July 28 - August 1	9.8	3.7	2.65 : 1.0
August 25 - 29	19.3	4.1	4.71 : 1.0
September 23 - 27	10.2	9.2	1.11 : 1.0
October 21 - 25	7.8	3.0	2.60 : 1.0
November 25 - 30	7.6	5.4	1.41 : 1.0
December 14 - 18	3.3	5.7	0.58 : 1.0
April 1 - December (Yearly Average)	8.9	4.4	2.02 : 1.0
June-November Average	10.8	4.2	2.58 : 1.0

Data source:

Taken from Glooschenko et al., 1974 (Eastern Basin data deleted).

TABLE 61. CLEAR SCOR/UNESCO CHLOROPHYLL *a* CONCENTRATIONS BASED ON STATIONS SIMILAR TO GLOOSCHENKO'S 1970 SURVEY (SURFACE AND MID-VALUES ONLY)

Year	Cruise	Western	Central	Basin Ratio W : C
1974	1	5.36	4.68	1.15 : 1.00
	2	7.47	2.30	3.25 : 1.00
	3	15.16	1.94	7.81 : 1.00
	4	15.19	3.63	4.18 : 1.00
	5	11.09	5.13	2.16 : 1.00
	6	12.05	8.73	1.38 : 1.00
	Yearly Average (n = 6)	11.05	4.40	2.51 : 1.00
	June-Nov Average (n = 5)	12.34	4.35	2.84 : 1.00
1975	1	13.27	6.20	2.14 : 1.00
	2	14.10	1.82	7.75 : 1.00
	3	12.05	2.85	4.23 : 1.00
	4	15.87	8.20	1.94 : 1.00
	5	10.74	10.34	1.04 : 1.00
	6	8.28	8.82	0.94 : 1.00
	Yearly Average (n = 6)	12.39	6.37	1.95 : 1.00
	June-Nov Average (n = 4)	13.19	5.80	2.27 : 1.00

The central basin chlorophyll a trends for 1970, 1974 and 1975 were similar (Figure 82). The bimodal peaks occurred during the spring and early fall, and a summer minimum was evident all three years. The magnitude of the high and low values found each year were similar, with differences due to cruise scheduling and fluctuations in the standing crop. The greatest increase in the average June to November chlorophyll a concentration occurred between 1974 (4.35 µg/l) and 1975 (5.80 µg/l). The central basin showed an estimated concentration increase of 38 percent from 1970 to 1975.

The western basin chlorophyll a concentrations were high throughout the summer months all three years (Figure 83). The average June to November chlorophyll a concentration was lowest in 1970 (10.82 µg/l), while in 1975 the average was 13.19 µg/l. This represented an estimated increase of 2.37 µg/l or 22 percent from 1970 to 1975.

If all CLEAR western and central basin stations and all depths were utilized for comparison with Glooschenko's 1970 study, the increase is even greater (Table 62). The 1975 June to November western basin chlorophyll a average would be 18.26 µg/l, representing a 7.44 µg/l or 84 percent estimated increase in the western basin chlorophyll a concentration from 1970 to 1975. An estimated increase of 2.04 µg/l or 46 percent was calculated for the central basin from 1970 to 1975 based on this comparative technique. This large increase can be partially attributed to a more intensive lake coverage in 1974 and 1975 particularly along the shorelines of the central basin and a more thorough coverage of the western basin. The observed increase can be attributed to several factors such as year to year fluctuations, meteorological influences and continued enrichment of the lake. The factors most responsible for the observed increase can best be determined from continued yearly studies. Comparisons of chlorophyll a data taken from several investigations are difficult to evaluate because of differing analytical techniques, sampling schedules and sampling locations (Tables 58 and 59). Therefore, trends based on such comparisons must be viewed conservatively.

Trophic Status

Various trophic classification systems have been proposed based on chlorophyll a concentrations. Three such classification systems were examined to evaluate the degree of eutrophication of Lake Erie. Glooschenko and Dobson (1975) established eutrophication classifications based on chlorophyll a data from the Great Lakes. Talling (1961) devised a classification system applicable to marine investigations. Sakamoto (1966) studied a series of Japanese lakes ranging from 4.5 to 65 m in depth from which he developed a method for determination of trophic status. The three classifications were as follows:

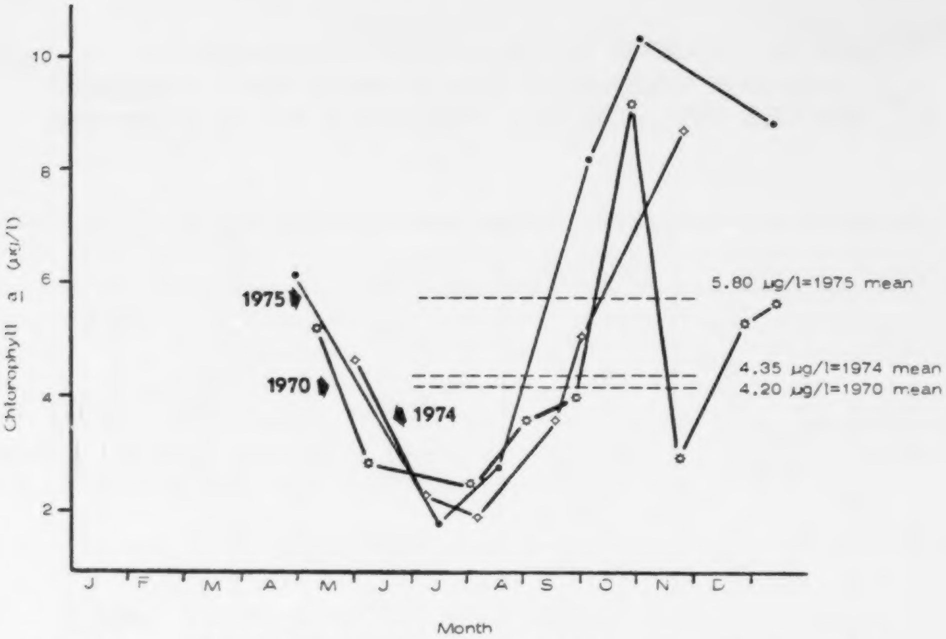


Figure 82. Comparison of central basin chlorophyll a values from Glooschenko's 1970 data and corresponding 1974 and 1975 data.

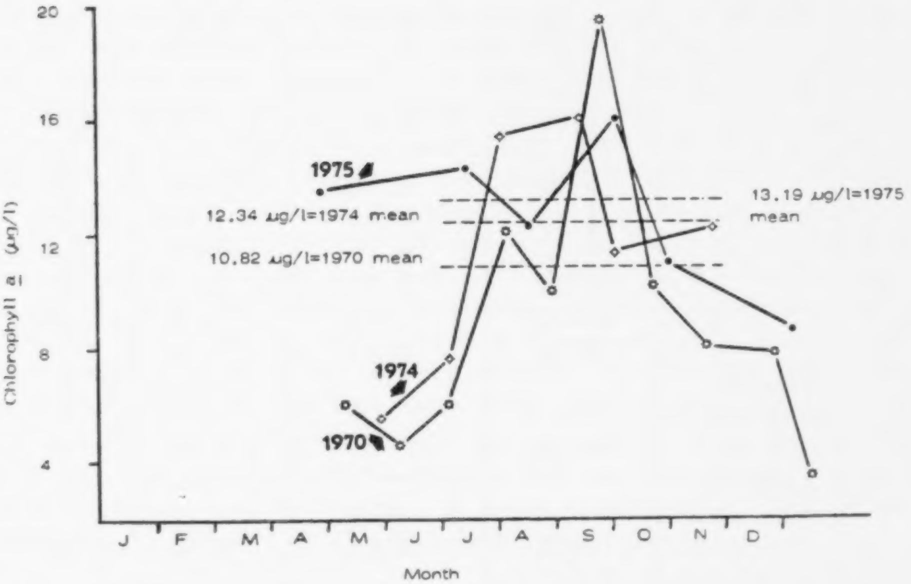


Figure 83. Comparison of western basin chlorophyll a values from Glooschenko's 1970 data and corresponding 1974 and 1975 data.

TABLE 62. CLEAR SCOR/UNESCO CHLOROPHYLL a (µg/l) VOLUME WEIGHTED CONCENTRATIONS. BASIN VALUES INCLUDE ALL STATIONS AT ALL DEPTHS

Year	Cruise	Western	Central	Basin Ratio W : C
1973	1	10.42	2.93	3.56 : 1.00
	2	13.70	3.91	3.50 : 1.00
	3	16.15	8.97	1.80 : 1.00
	Yearly Average	13.42	5.27	2.55 : 1.00
1974	1	9.78	3.85	2.54 : 1.00
	2	10.93	2.80	3.90 : 1.00
	3	18.24	2.73	6.68 : 1.00
	4	18.84	4.34	4.34 : 1.00
	5	15.45	4.70	3.29 : 1.00
	6	14.46	10.33	1.40 : 1.00
	Yearly Average (n = 6)	14.62	4.79	3.05 : 1.00
	June-Nov. Average (n = 5)	15.58	4.98	3.13 : 1.00
1975	1	11.92	6.19	1.93 : 1.00
	2	22.53	2.95	7.64 : 1.00
	3	18.14	3.26	5.56 : 1.00
	4	18.09	8.23	2.20 : 1.00
	5	14.26	10.53	1.35 : 1.00
	6	6.03	8.21	0.73 : 1.00
	Yearly Average (n = 6)	15.16	6.56	2.31 : 1.00
	June-Nov. Averages (n = 4)	18.26	6.24	2.93 : 1.00

	Sakamoto	Talling	Glooschenko and Dobson
Eutrophic	5-140 µg/l	30 µg/l	5-10 µg/l
Mesotrophic	1-15 µg/l	1-30 µg/l	5 µg/l
Oligotrophic	0.3-2.5 µg/l	1 µg/l	

The yearly average volume-weighted corrected chlorophyll a concentrations for each sub-basin were used to evaluate the three classification systems. When Glooschenko and Dobson's system was applied, the western basin, Sandusky sub-basin and western central basin were found to be eutrophic, while the eastern central basin was judged mesotrophic. According to Sakamoto's classifications the western basin and Sandusky sub-basin were eutrophic and the entire central basin was considered mesotrophic. With the criteria developed by Talling, both the western basin and central basin were considered mesotrophic.

Of the types of investigations used to establish each of the classification systems, the Glooschenko-Dobson system, developed from using Great Lakes data, seems to be the most applicable to Lake Erie.

Particulate Organic Carbon versus Chlorophyll a

During the last cruise of 1973 and all cruises in 1974 and 1975, calculations and tonnages of particulate organic carbon (POC) were determined at all stations sampled. The western basin concentrations (Figure 84) and tonnages (Figure 85) of POC and corrected chlorophyll a both demonstrated an increase during the summer months and a decrease in the fall. In the central basin both chlorophyll a and POC decreased from the spring phytoplankton pulse through mid-summer and increased in the late summer and early fall. During the December cruise of 1975 an inverse chlorophyll a - POC relationship was evident in the central basin. It was felt that as a result of the high winds occurring in the late fall, detrital POC was resuspended from the sediments. During this period, chlorophyll a concentrations decreased due to the suboptimal conditions for phytoplankton growth. Central basin surface and bottom area-weighted concentrations of particulate phosphorus (PP), POC and corrected chlorophyll a were examined (Figures 86 and 87). It was apparent especially in the surface waters that decreases and increases in chlorophyll a were accompanied by corresponding changes in PP and POC until December (Cruise 6).

Ratios of pheopigment to corrected chlorophyll a, corrected chlorophyll a to POC and PP to POC were used to examine the effect of resuspension on chlorophyll a concentrations (Figures 88 and 89). The spring

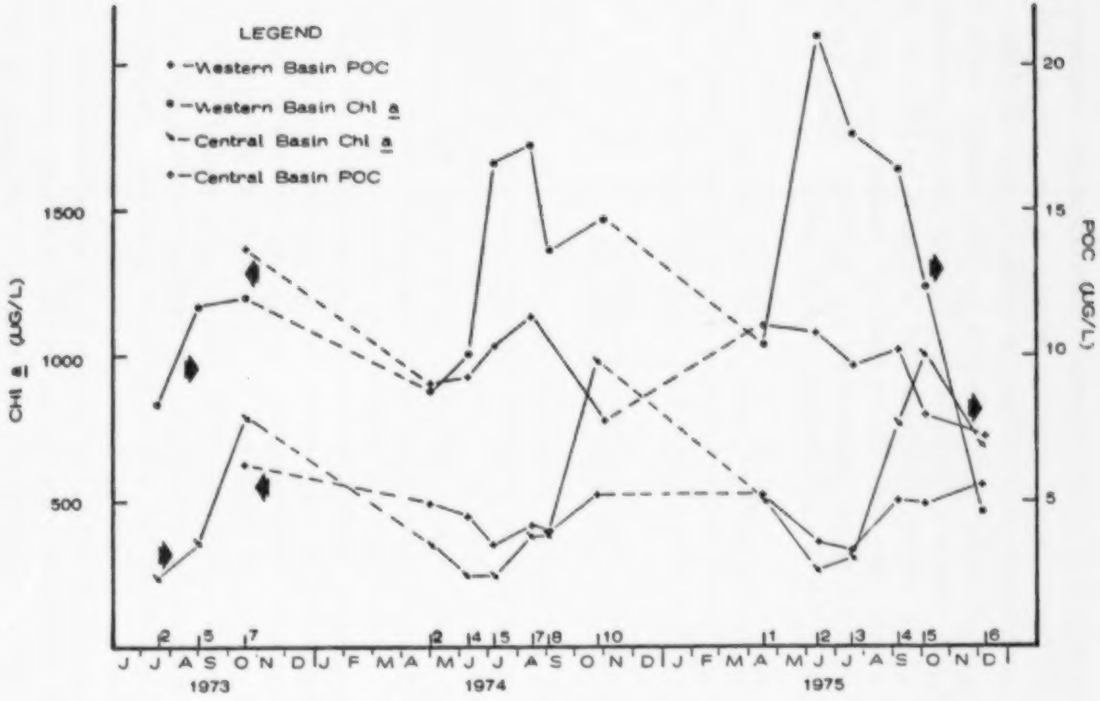


Figure 84. Particulate organic carbon and corrected chlorophyll a concentrations - Lake Erie central and western basins, 1973-1975.

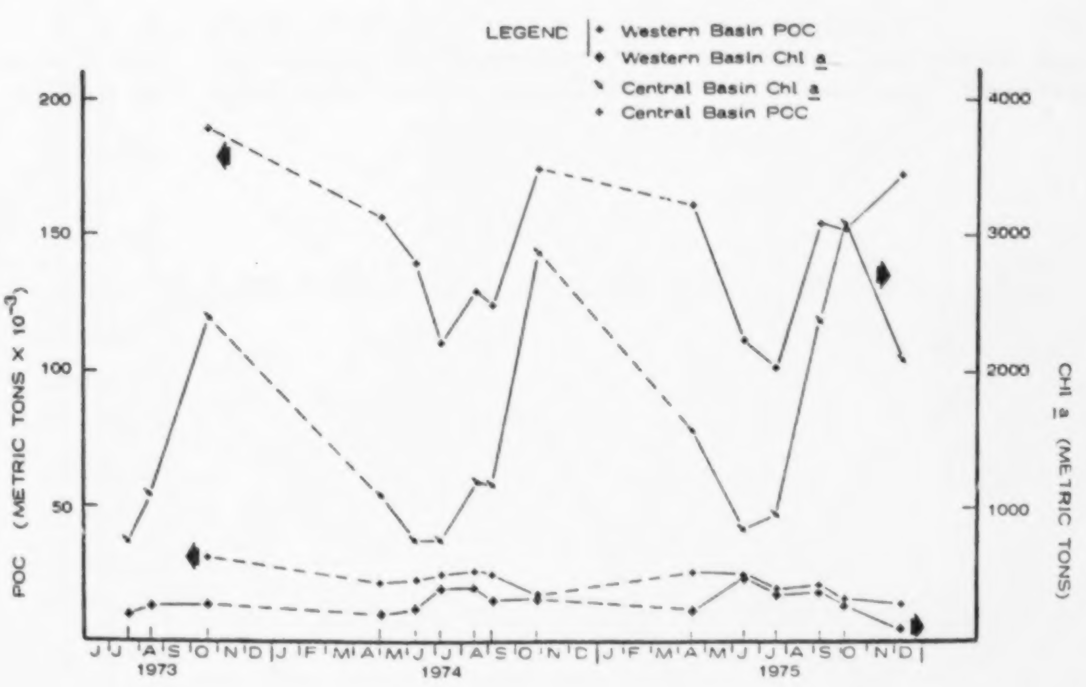


Figure 85. Particulate organic carbon and corrected chlorophyll a tonnages, Lake Erie central and western basins, 1973-1975.

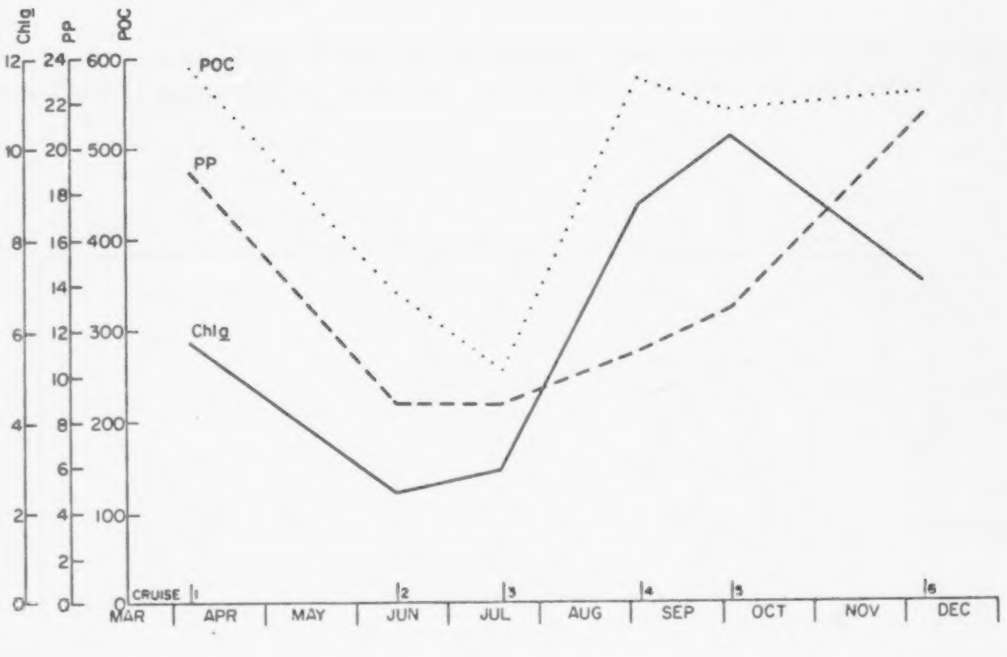


Figure 86. Lake Erie central basin surface water - 1975: corrected chlorophyll a, particulate phosphorus and particulate organic carbon concentrations, area weighted.

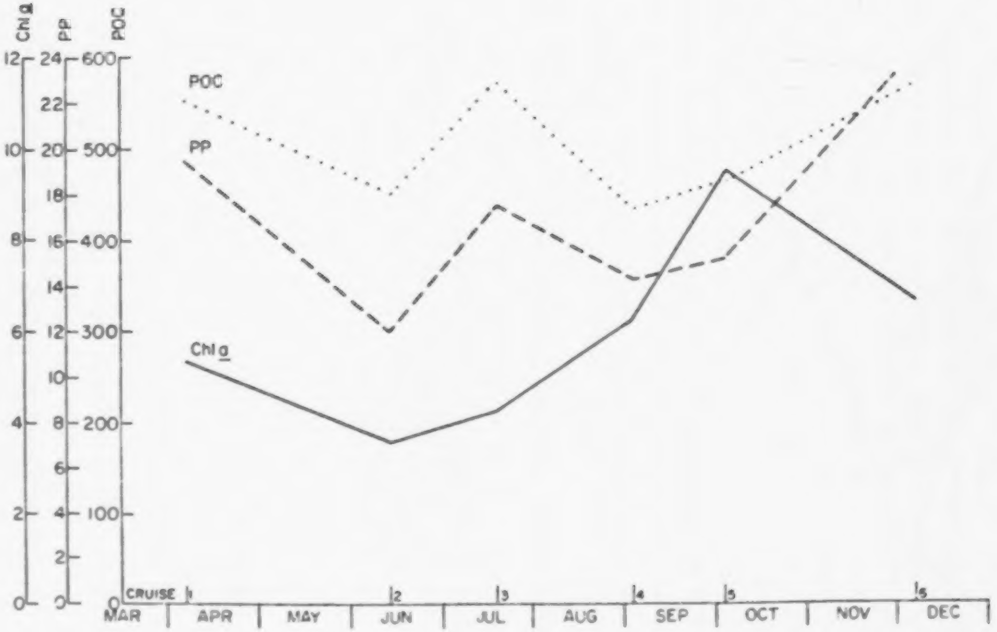


Figure 87. Lake Erie central basin bottom water - 1975: corrected chlorophyll a, particulate phosphorus and particulate organic carbon concentrations, area weighted.

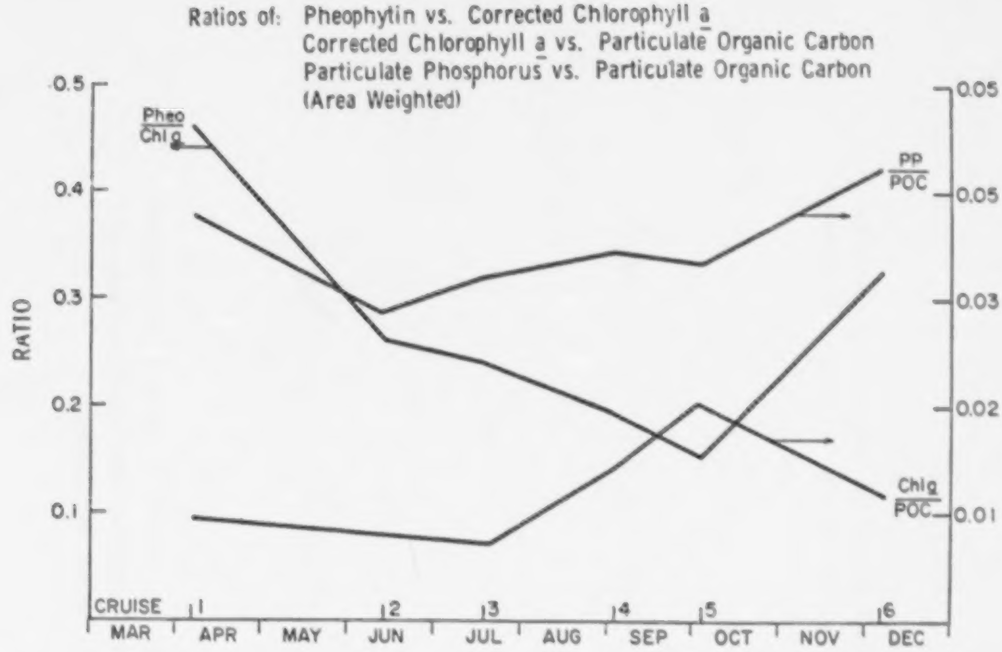


Figure 88. Lake Erie central basin bottom water - 1975.

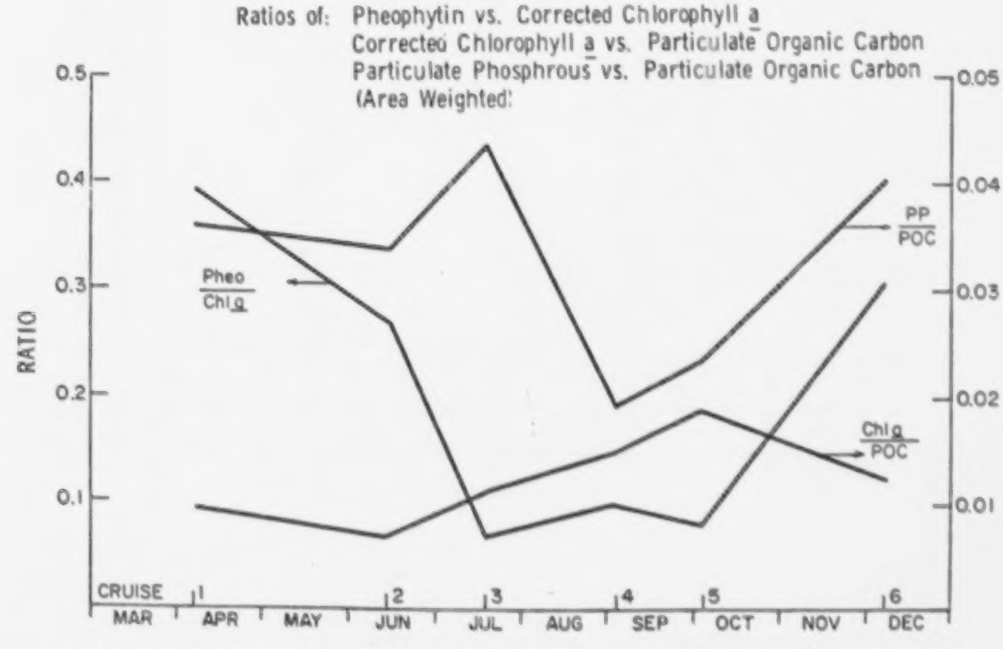


Figure 89. Lake Erie central basin surface water - 1975.

and fall were periods of the highest pheopigment to corrected chlorophyll a ratios, indicative of a resuspension of detritus containing pheopigment. During the same periods, the PP to POC ratio was also high. It was assumed the PP as well as POC was resuspended from the sediments; however, the large quantities of PP were not necessarily of an organic nature. The chlorophyll a to POC ratio was low during the fall due to the decrease in chlorophyll a and an increase in POC. The highest chlorophyll a to POC ratio occurred during the late summer and corresponds to to the highest standing crop in the central basin. During this same period, the pheopigment to corrected chlorophyll a ratio was the lowest, indicative of a larger portion of the chlorophyll a associated with viable cells. It was evident that the correlation between corrected chlorophyll a and POC, and to a less degree PP, was quite strong during the stratified period, but not during unstratified periods. This poor correlation was attributed to resuspension of previously settled plankters which had undergone various degrees of decomposition. The increase of pheopigments and POC strengthens this conclusion. It is also possible that chlorophyll a not associated with viable cells is resuspended. If this occurs, the biomass estimates based on chlorophyll a and POC may be misleading during periods of extensive resuspension.

Summary and Conclusions

1. As a segment of the Lake Erie nutrient study 1973, 1974 and 1975, corrected chlorophyll and pheopigment concentrations were determined at 51 stations in the western and central basins. Of the 2,332 corrected chlorophyll a measurements taken, 98 percent of the values ranged between 0.34 and 29.12 µg/l. The mean of these observations was 7.50 µg/l.

2. The spectrophotometric technique recommended by SCOR/UNESCO (1966) was utilized for the analytical procedure. Concentrations of chlorophylls a, b and c were calculated according to SCOR/UNESCO along with corrected chlorophyll a, pheopigment a and the Fo/Fa ratio described by Lorenzen (1967). Only corrected chlorophyll a and pheopigment a were discussed in detail.

3. The quantitative effects of basin, station, cruise, sampling depth and stratification have been determined with analysis of variance models. Of these variables, basin was considered a first order effect, while station within basin and cruise had second order effects.

4. The seasonal trends of chlorophyll *a* differed in the western and central basins. Due to different physical, chemical and biological factors influencing these two basins, they exhibit different seasonal patterns. The western basin maintained highest chlorophyll *a* concentrations during the summer months, while the central basin exhibited two peaks, one in the early spring and the other following turnover in the late summer (early fall).

5. The June to November mean concentration of corrected chlorophyll *a* was shown to increase yearly from 1973 to 1975. The maximum increase in tons for the central basin was 38 percent, which occurred in 1975, while the maximum increase for the western basin of 44 percent was observed in 1974.

6. Long-term chlorophyll trends are difficult to evaluate. Lake Erie chlorophyll surveys have been undertaken by the Federal Water Pollution Control Administration (FWPCA, 1968) in 1967 and 1968 and by Glooschenko in 1970 (Glooschenko, et al. 1974). The FWPCA survey substantiated the year to year chlorophyll increases observed in the 1970's. The increase in chlorophyll *a* concentration over the nine-year period (June to November 1967 to 1975) was 7.08 ug/l or 146 percent. Due to an apparent analytical problem the FWPCA data was of questionable reliability. When Glooschenko's 1970 survey was compared with the corresponding CLEAR survey a 38 percent increase in the central basin chlorophyll *a* concentrations was estimated between 1970 and 1975. Thirty-three percent of the increase occurred between 1974 and 1975. The western basin showed an estimated 22 percent increase between 1970 and 1975, with the greatest increase observed from 1974 to 1975.

7. The western basin and the western half of the central basin were considered eutrophic based on criteria of the chlorophyll trophic classification system established by Glooschenko and Dobson (1975). The eastern half of the central basin was considered mesotrophic.

8. The relationships of particulate organic carbon to chlorophyll a and pheopigment to chlorophyll a were examined during 1975, in order to evaluate the effects of resuspension. Particulate organic carbon and pheopigments were found to increase during periods of maximum resuspension, while chlorophyll concentrations decreased. This would indicate that during the spring and fall periods of high winds, detrital material is resuspended contributing to the particulate organic carbon and pheopigments in the water column.

9. The drawbacks involved in the chlorophyll technique have been discussed throughout the text. Errors involved in the analytical portion of the technique have been calculated. Measurement errors are negligible, and error due to extended periods of storage present the greatest analytical error. Determination of chlorophyll concentrations from samples freeze stored for more than two months may yield concentrations that underestimate the actual values.

   In calculating volume-weighted tons of chlorophyll it was assumed that the horizontal distribution of chlorophyll was consistent within a grid. Patchiness of phytoplankton does occur, thereby resulting in patchy chlorophyll concentrations. Error in chlorophyll analysis as a result of patchiness seems inevitable but has not been quantified.

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SECTION 8

PRIMARY PRODUCTIVITY SURVEY OF THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

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INTRODUCTION

Within the last twenty years biologists have observed that man has increased the nutrient input of Lake Erie to cause significant changes in its flora and fauna (Beeton and Edmondson 1972). From 1938-1964, total phytoplankton concentration in the island area increased by 3.5 times, and the dominant phytoplankton changed from diatoms to blue-green algae. From 1920-1962 in central Lake Erie, phytoplankton numbers increased several fold during spring and autumn pulses.

Primary productivity is a measure of the rate of buildup of organic compounds from the energy that is transferred to successive trophic levels. Ths photosynthetic process is responsible for the greater part of this buildup in most environments (Goldman 1963). Estimates of primary productivity for Lake Erie first appeared in 1949, when Verduin (1951) measured the rates of CO_2 removal per unit of phytoplankton volume per hour in western Lake Erie. Verduin concentrated phytoplankton by passing lake water through bolting cloth and placed these samples in bottles under an optimal light intensity of 400 foot candles (fc). However, he estimated that about two-thirds of the photosynthetic organisms escaped concentration (Verduin 1956). Consequently, since 1957 he has used natural phytoplankton densities and has estimated rates of Co_2 removal in open-lake conditions. He found that under these conditions photosynthetic rates exceed those rates obtained from bottle experiments by two times (Verduin 1960 and 1962). For these reasons his more recently published rates of 3070 mg absorbed per m^2 per day for net photosynthesis and 6160 mg C absorbed per m^2 per day for gross photosynthesis are used for comparison to the results of subsequent studies.

Saunders (1964) made the first estimates of primary productivity in Lake Erie with ^{14}C at a single station in the western basin in 1957; estimates were 68.3 mg C/m^3 per day for net and 142.9 mg C/m^3 per day for gross photosynthesis. He converted these estimates to 97.6 and 371.5 mg C/m^2 per day, respectively, for net and gross daily integral photosynthesis by using a formula derived by Rodhe, Vollenweider and Nauwerck (Saunders 1964).

Further primary productivity work was done on Lake Erie in 1968 when Porkso et al. (1969) took a one-day cruise along the entire lake to make the first estimates of primary productivity for central Lake Erie. With the ^{14}C technique and a shipboard incubator (light intensity = 1000 foot candles, temperature = 60°F), Parkos et al. (1969) found surface rates of 127.7 mg C/m^3 per hour at one station in the western basin and 42.4-54.7 mg C/m^3 per hour at two stations in the central basin. In 1969 and 1970, Cody (1972) used ^{14}C and found extremely variable rates, from 11-5470 mg-atoms C [132-65,640 mg C] per m^2 per day, in western Lake Erie during _in situ_ studies at ten stations. Glooschenko et al. (1974) made intensive measurements in Lake Ontario and all three basins of Lake Erie (25 stations) by calibrating a shipboard incubator (light intensity = 8000 lux, temperature = surface water temperature) with simultaneous _in situ_ experiments. Surface water productivity obtained from the incubator for each station was converted to an _in situ_ estimate for the entire water column. Mean values for ten cruises in 1970 were 30-4760 mg C/m^2 per day and 120-1690 mg C/m^2 per day for the western and central basins respectively.

This report includes data for the central and western basins of Lake Erie that were obtained during July-October 1974. The objectives of the study were to investigate, by means of the ^{14}C method and shipboard incubation of samples, the vertical, horizontal and temporal distribution of primary productivity in central and western Lake Erie and to compare data obtained in 1974 with data from previous investigations. Samples were taken from five western basin stations and eleven central basin stations during cruises abourd the _R/V Hydra_--26 July-6 August (Cruise 6), 12 August-19 August (Cruise 7), 26 August-7 September (Cruise 8), and 21 October-1 November (Cruise 10, Figure 90).

Between cruises, a location approximately 250 m offshore, south of The Rattles of Rattlesnake Island in western Lake Erie was chosen for _in situ_ experiments. Cody (1972) reported ranges of 16.7-185.4

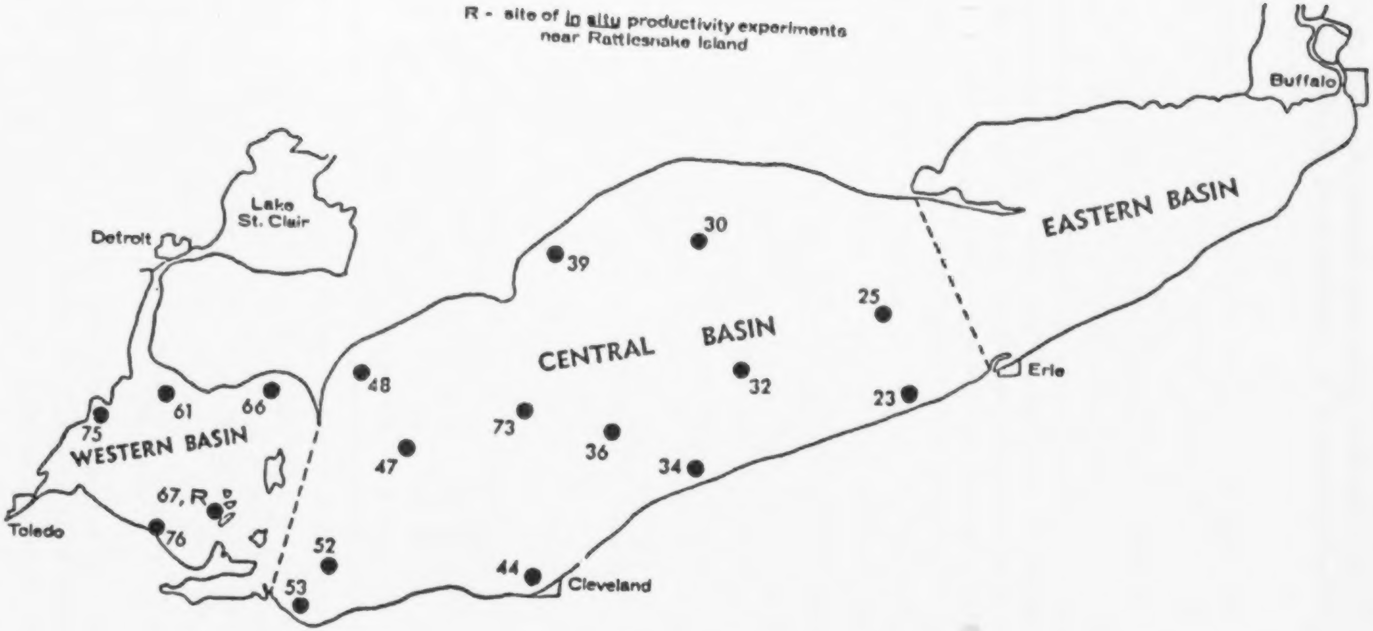
R - site of in situ productivity experiments
near Rattlesnake Island
Buffalo
EASTERN BASIN
Lake
St. Clair
Detroit
30
39
25
CENTRAL BASIN
Erie
48
32
23
61
66
75
73
WESTERN BASIN
47
36
34
67, R
Toledo
76
52
44
53
Cleveland

Figure 90. Map of Lake Erie showing station locations in the central and western basins.

mg-atoms C [200-2225 mg C] per m^3 per hour, 36.1 - 654.9 mg-atoms C [433-7859 mg C] per m^2 per hour, and 240-5470 mg-atoms C [2880-65,640 mg C] per m^2 per day for optimal, integral, and daily integral primary productivity, respectively, at Rattlesnake Island in 1970.

PROCEDURES

Field Methods

At each station submarine photometer readings were taken at one-meter intervals from lake surface to bottom, or until the light meter read zero. The reading made when the photometer was suspended just above the water represented surface light intensity. Samples of lake water were collected from one meter and from a depth of about one percent of the surface light intensity, which represented the lower limit of the euphotic zone. Samples were also collected from intermediate levels (commonly three meters and five meters), depending upon the thickness of the euphotic zone.

Sample preparation follows the method of Goldman (1963). A sample of lake water, taken with a five-liter Niskin sampling bottle, was transferred to 300-ml BOD bottles, two light and one dark for each depth. The dark bottles were wrapped with a double layer of black electrical plastic tape. A layer of aluminum foil covered the tape to prevent heat buildup. Two layers of foil covered the stopper to keep out light. Between cruises both dark and light bottles were washed with concentrated HNO_3 and thoroughly rinsed with tap water with a final rinse of distilled water. The bottles were inverted and air dried.

A fresh stock solution of ^{14}C was prepared daily by combining the contents of ampules of sodium bicarbonate - ^{14}C ($NaH^{14}CO_3$) in sterile aqueous solution with pH = 9.5, which was supplied in the amount of 5.0 μCi/5.0 ml per ampule by New England Nuclear Corp. Approximately 1.0 ml of the stock solution was added to each BOD bottle by means of a 2-ml hypodermic syringe (accuracy = ± 5 percent) with a 15-cm 18-gauge needle. The stock solution was added to the bottom of the bottle, and the syringe was rinsed gently with water from the top of the bottle. The activity of the $NaH^{14}CO_3$, added via the syringe, was taken to be 1.0 μCi (2.22×10^6 ± 10 percent disintegrations per minute) as determined by New England Nuclear Corporation.

After innoculation, the bottle contents were thoroughly mixed, and the bottles were placed in a shipboard incubator for three to five hours. Light intensity of approximately 9000 lux was provided by a bank of six daytime fluorescent lamps. Surface water was continuously circulated through the incubator. After incubation the bottle contents were mixed, 10 ml of material was removed with a repipet, and 10 ml merthiolate solution was added to stop further ^{14}C uptake. The bottle contents were thoroughly mixed.

Since the relative activity of the plankton was unknown when experiments were begun, the investigator concentrated as much material as possible from a bottle onto a membrane filter. As more material is added, sample counting time decreases linearly, unless the additional material decreases detection of the -particles emitted from ^{14}C. In areas with high concentrations of suspended particles, filter pores clogged within approximately ten minutes. In some areas (e.g., Stations 30, 47, and 73), the entire bottle content was passed through the filter within ten minutes; in other areas (notably Stations 61, 75, and 76) aliquot was used since the filtration time for the entire content would have exceeded ten minutes. Material from each BOD bottle was vacuum-filtered onto a 25-mm diameter Gelman GA-6 Metricel membrane filter (pore size 0.45 u). The filtration apparatus aboard the R/V Hydra consisted of a vacuum manifold that held four filter funnels so that the contents of as many as four BOD bottles could be filtered simultaneously. Vacuum pressure did not exceed 300 mm Hg. Since the membrane filters differ in rates of water absorption, all filters were presoaked in distilled water to decrease filtration time. Once the material had been concentrated on the membrane filter, the filter was rinsed with approximately 25 ml of 0.003 N HCl to remove any ^{14}C that may have accumulated on the surface of the filtered material; a rinse of 25 ml filtered lake water (if available) or distilled water followed. The membrane filter was then attached with household glue to a 32-mm diameter stainless steel planchet. Water retained by the filtered material absorbs the -particles emitted from ^{14}C, so filters were stored in pillboxes and assayed several weeks later.

Radioassay

Filters were assayed with a thin end-window gas-flow detector; gas composition was approximately 0.9 percent isobutane in 99.1 percent helium. Planchets were loaded onto a Nuclear Chicago Corp. Model No. C-110B automatic sample changer. A Nuclear Chicago Corp. Model 181A scaler recorded the counts per measurement, and a Nuclear Chicago Corp. Model No. C.111B printing timer recorded the time required for the measurement. A 0.0875 μCi ^{14}C standard source was used to calculate counter yield by the formula of Arena (1971):

$$Y = cpm/dpm,$$

where Y is counter yield, cpm is observed count rate of the standard (counts per minute), and dpm is the calibrated activity of the standard (disintegrations per minute). Counter yield was 16-17 percent. Light bottles were counted a minimum of 10,000 counts (± 2.1 percent probable error at $P = 0.05$) and dark bottles a minimum of 1000 counts (± (± 6.4 percent probable error at $P = 0.05$). One thousand counts per measurement for dark bottles was chosen to reduce sample counting time to about ten minutes. The discrepancy between light and dark bottle counting statistics is discussed later.

Primary Productivity Calculation

Incubator productivity was calculated by an expanded formula developed by Saunders, et al. (1962). Dark bottle incubator productivity was subtracted from light bottle incubator productivity to correct for nonphotosynthetic uptake of ^{14}C. The corrected incubator productivity (mg $C/m^3 \cdot h$) was converted to integral productivity (mg $C/m^2 \cdot h$) by the relationship reported by Glooschenko et al. (1974):

$$\frac{mg\ C/m^2 \cdot h}{mg\ C/m^3 \cdot h} = 1.85x,$$

where mg $C/m^2 .h$ is integral productivity, mg $C/m^3 .h$ is incubator productivity, and x is Secchi disc depth in meters; the relationship is solved for mg $C/m^2 \cdot h$. Since the incubator productivity of Glooschenko et al. (1974) is based on a composite sample from one-meter and five meter depths, incubator productivities from one-meter and five-meter depths in this report were averaged, and the mean value was inserted into the above relationship. Integral productivity was converted to daily integral productivity (mg $C/m^2 \cdot$ day) by the method of Glooschenko et al. (1974).

In situ Productivity

Procedure for *in situ* productivity experiments near Rattlesnake Island was similar to the shipboard method except incubation. Photometer readings and Secchi disc depth were determined as previously described. Temperature was measured by means of a YSI Model 51A dissolved oxygen meter equipped with a YSI 5450 probe. Lake water was collected with a three-liter non-metallic Kemmerer water sampling bottle. For the one-meter depth, one intermediate depth, and the bottom sampling depth, pH was measured in the laboratory on South Bass Island within two hours of collection, and total alkalinity was determined within four hours of collection. Upon innoculation with one microcurie of $NaH^{14}CO_3$, one light and one dark bottle were suspended in the lake at the depth from which the water was taken. The incubation apparatus consisted of an anchored nylon line with an attached float on the lake surface. Aluminum strips were tied to the line at the proper depths. The BOD bottles were attached to the strips by shower curtain hooks that fastened to hose clamps at the necks of the bottles. If possible, the samples were fixed when the bottles were retrieved from the line; when the weather was rough, they were fixed at the laboratory approximately half an hour after retrieval. Samples were filtered at the South Bass Island laboratory or aboard the _R/V Hydra_, and the membrane filters were prepared for gas-flow counting.

In situ primary productivity (mg $C/m^3 \cdot h$) at each sample depth was calculated. These estimates were then plotted against depth on graph paper. Integral _in situ_ productivity (mg $C/m^2 \cdot h$) was calculated by determining the area beneath the productivity-depth curve with a planimeter.

Correction Factors

The filtered material absorbs energy from the β-particles emitted from ^{14}C and prevents the escape and subsequent detection of some of the particles by counting equipment. Lower sample count rate and, therefore, lower productivity result. An experiment was performed to determine whether this self-absorption of β-particles occurred in filtered material during the 1974 season. Lake water from a depth of one meter in Put-in-Bay Harbor was collected with a Kemmerer water sampling bottle on 5 October 1974. The water was transferred to six clear BOD bottles, and approximately one microcurie of $NaH^{14}CO_3$ was was added to each bottle. After the contents were thoroughly mixed, the the bottles were incubated approximatly four hours in the shipboard incubator. After incubation the contents were fixed as previously described. Aliquots of 25, 50, 75, and 100 ml from each bottle were filtered onto membrane filters as described. Because filtration of the 100-ml aliquots required approximately ten minutes, these volumes were assumed to represent the denser concentrations of material collected over the season. Filters were rinsed and processed for gas-flow counting as in the productivity experiments. Filters were counted 10,000 counts minimum. Sample count rate was corrected to actual

^{14}C uptake. Carbon-fourteen uptake (dpm) was divided by aliquot volume (ml) and duration of incubation (h), and the result (dpm/ml per hour) was plotted against aliquot volume.

Strickland and Parsons (1968) stated that the fixative formaldehyde at a concentration of 0.3 percent volume may influence the excretion or loss of fixed ^{14}C from the more delicate marine algae. The effect of merthiolate upon sample activity was studied, as merthiolate may also cause ^{14}C loss from phytoplankton. Lake water collected on 16 September from one meter below the surface of Put-in-Bay Harbor was added to six clear 300-ml BOD bottles. About one microcurie $NaH^{14}CO_3$ was added and the bottles were incubated approximately four hours in the shipboard incubator. Samples were fixed as in the productivity experiments. At intervals of 1, 2, 4, 8, 16, and 24 hours after fixation 50-ml aliquots from each BOD bottle were filtered onto membrane filters. The filters were prepared for gas-flow counting. The experiment was run again on 19 October 1974, and aliquots were filtered at intervals of 0, 1, 2, 4, 8, and 16 hours after fixation. During both experiments bottles were stored overnight and filtered the next day. Filters were counted 10,000 counts minimum. Graphs were drawn of carbon-fourteen uptake per ml per hour vs. time after fixation for the twelve bottles.

Relative light intensity in the incubator was measured while the research vessel was docked at Put-in-Bay on 19 September 1974. The incubator was divided into nine horizontal zones, and several photometer readings were taken at each zone to represent light intinsity at clear water, mid-lake central basin stations, as the water had been standing for several days. Photometer readings were repeated after the water had been circulated for two hours, which approximated turbid stations. Whether or not relative light intensity was reduced by use of a clear plexiglass top when the lake was rough was also determined. A mean relative light intensity value for any position in the incubator during each set of conditions was determined by averaging individual measurements at each location in the incubator.

RESULTS AND DISCUSSION

Incubator, integral, and daily integral productivity in 1974 were, respectively, 4.1-124 mg C/m^3 per hour, 16-364 mg C/m^2 per hour, and 140-4370 mg C/m^2 per day for western Lake Erie and 5.1-51.2 mg C/m^3 per hour, 44-242 mg C/m^2 per hour, and 530-2180 mg C/m^2 per day for central Lake Erie (Table 63). Results of calculations using Glooschenko's relationship are presented in Table 64.

Maximum incubator productivity in 1974 agrees to within 3 percent of that reported by Parkos et al. (1969) and 16 percent of the maximum mean productivity per cruise reported by Vollenweider et al. (1974) for western Lake Erie (Table 63). Maximum central basin incubator productivity in 1974 is 2.4 times greater than the mean productivity per cruise reported by Vollenweider, but the difference may be in the comparison of mean values per cruise to a range of values for the entire season of 1974. Parkos et al. (1969) report productivity 7 percent greater than the maximum incubator productivity found during this study.

Daily integral productivity reported by Saunders (1964) is relatively low when compared with other western basin estimates in Table 63, but this probably is explained by his sampling one site late in the year. The lower limit of Verduin's estimates fall within the daily integral productivity range calculated in 1974. Cody's (1972) mean estimate of 10,000 mg C/m^2 per day is 2.3 times greater than the maximum daily integral productivity in the western basin in 1974.

Central Lake Erie incubator productivity for late July averaged 1.7 times mid-August values and 0.7 times late October values (Table 65). Nutrient release upon fall overturn (Gächter et al. 1974) probably resulted in the October maximum. Mean incubator productivity for western Lake Erie decreased from late July to late October with the July value being 1.4 and 1.6 times greater than September and October values respectively. Integral productivity for central Lake Erie followed the trend of incubator productivity with the late July value being 1.2 times the August value and 0.9 times the October value. Western Lake Erie integral productivity in July was 2.4 and 1.7 times September and October integral productivity, respectively.

TABLE 63. COMPARISON OF PRIMARY PRODUCTIVITY MEASUREMENTS IN CENTRAL AND WESTERN LAKE ERIE FROM 1957–1974

Date	Method	Incubation	mg C/m^3.h	mg C/m^2.h	mg C/m^2.day	Source
			Western basin			
1957–1962	pH–CO$_2$	natural conditions			net 3,070 gross 6,160	Verduin (1962)
1957 Oct.	^{14}C	*In situ*			net 96.7 gross 371.5	Saunders (1964)
1968 July	^{14}C	shipboard	127.7			Parkos, Olson & Odlaug (1969)
1969–1970	^{14}C	*In situ*	13.2–2225	18.0–7859	132–65,640 mean 10,000	Cody (1972)
1970 Apr–Dec.	^{14}C	*In situ*, shipboard	4.8–146.9^a	5.0–397^a	30–4,760^a	Vollenweider, Munawar & Stadelmann (1974)
1974 July–Oct.	^{14}C	*In situ*	3.6–152	95–342		Sheffield (1975)
	^{14}C	shipboard	4.1–124^b	16–364	140–4,370	
			Central basin			
1968 July	^{14}C	shipboard	42.4–54.7			Parkos, Olson & Odlaug (1969)
1970 Apr–Dec.	^{14}C	*in situ*, shipboard	5.5–21.4^a	17–141^a	120–1,690^a	Vollenweider, Munawar, & Stadelman (1974)
1974 July–Oct.	^{14}C	shipboard	5.1–51.2^b	44–242	530–2,180	Sheffield (1975)

a range of mean values per cruise

b range of station means for productivity within euphotic zone

TABLE 64. CARBON ASSIMILATION RATES BY STATION AND CRUISE FOR CENTRAL AND WESTERN LAKE ERIE IN 1974

Date	Station	Mean Incubator Rate[a] (mg C/m^3.h + SE)	Integral Rate[b] (mg C/m^2.h)	Daily Integral Rate (mg C/m^2.day)
Cruise 6				
1 Aug	30	19.8 ± 1.5	130	1560
30 July	47	16.4 ± 1.6	180	2160
4 Aug	48	11.1 ± 1.2	83	1000
27 July	52	20.8 ± 3.3	109	1310
26 July	61	12.4 ± 1.3	37	440
28 July	66	33.0 ± 3.1	194	2330
27 July	67	33.5 ± 1.4	157	1880
30 July	73	17.3 ± 2.2	133	1600
26 July	75	124 ± 6	364	4370
26 July	76	98 ± 2	166	1990
Cruise 7				
13 Aug	23	8.3 ± 0.9	94	1130
13 Aug	25[c]	5.1 ± 0.4	84	1010
14 Aug	30[d]	8.1 ± 0.9	84	1010
15 Aug	34	10.1 ± 1.0	82	980
15 Aug	36[c]	7.2 ± 1.3	73	880
17 Aug	44	13.6 ± 0.8	124	1490
12 Aug	47	14.0 ± 0.7	154	1850
16 Aug	48	15.7 ± 0.9	135	1620
Cruise 8				
6 Sept	53	33.3 ± 2.2	44	530
7 Sept	61	30.4 ± 1.1	87	1040
6 Sept	67	31.0 ± 1.6	75	900
7 Sept	75	32.3 ± 2.3	57	680
7 Sept	76	76.8 ± 2.6	85	1020
Cruise 10				
23 Oct	23	23.1 ± 0.9	87	780
23 Oct	25	14.5 ± 0.5	82	740
26 Oct	30	18.4 ± 1.1	80	720
26 Oct	32	10.9 ± 0.6	69	620
27 Oct	36	18.6 ± 1.0	160	1440
27 Oct	39	17.0 ± 1.2	60	540
29 Oct	44	51.2 ± 1.2	242	2180
21 Oct	47	29.9 ± 1.6	216	1940
28 Oct	48	23.2 ± 0.9	172	1550
30 Oct	53	34.8 ± 0.9	123	1110
1 Nov	61	4.1 ± 0.1	16	140
29 Oct	66	28.1 ± 1.0	136	1220
30 Oct	67	46.0 ± 1.4	141	1270
21 Oct	73	30.3 ± 1.7	223	2010
1 Nov	75	77.6 ± 2.4	171	1540
31 Oct	76	26.4 ± 1.2	73	660

[a] average of all sample depths.

[b] incubator rates from 1 m and 5 m depths were averaged and the mean value inserted into the relationship found in Glooschenko et al (1974)

[c] includes sample from metalimnion.

[d] includes sample from hypolimnion.

TABLE 65. MEAN PRODUCTIVITY BY BASIN FROM JULY-OCTOBER 1974

No. of Stations	Basin	Incubator Productivity (mg $C/m^3.h \pm SE$)	Integral Productivity (mg C/m^2 .h)	Daily Integral Productivity (mg C/m^2.day)
Cruise 6				
5	central	17.1 ± 1.7	127	1530
5	western	60 ±22	184	2200
Cruise 7				
8	central	10.2 ± 1.3	104	1250
Cruise 8				
4	western	42.6 ± 11.4	76	910
Cruise 10				
11	central	24.7 ± 3.4	138	1240
5	western	36.4 ±12.3	107	960

Horizontal distribution of incubator productivity follows that of previous investigators. Parkos et al. (1969) and Glooschenko et al. (1974) report a west to east gradient in Lake Erie with the highest productivity in the western end. A north to south gradient in both basins during 1970 (Glooschenko et al. 1974) is not quite as evident during 1974. The maximum productivity in mid-summer in western Lake Erie reported by Glooschenko occurred in 1974. However, upon examination of his monthly distribution maps (Glooschenko et al. 1974, Figure 95), one finds that the estimates of 124 mg $C/m^3 \cdot h$ reported in July 1974 for Stations 75 and 76 are nearly double those reported for the summer 1970.

Results of three in situ experiments near Rattlesnake Island show that when productivity (mg $C/m^3 \cdot h$) is plotted against relative light intensity, three distinct curves result (Figure 91). Primary productivity on 10 September remained linear through a relative light intensity at least 2.5 times greater then that for 21 July and 6 October. In October, when surface light intensity and water temperatures are lower, phytoplankton survive at lower light intensities than in July and September. Primary productivity in October leveled off more rapidly than in July and September.

For each of the three in situ experiments the primary productivity vs. depth curve has a slope similar to its corresponding light transmission curve (Figure 92). Maximum productivity occurred at approximately one meter. Cody (1972) reported maximal productivity in western Lake Erie from one to three meters and rarely at depths shallower than one meter.

For a series of increasing volumes of filtered phytoplankton, self-absorption of β-particles from ^{14}C exists if a decrease in dpm/ml per hour occurs. Results of the self-absorption experiment (Figure 93) indicate that there was no decrease in dpm/ml per hour, although results from individual bottles varied. No correction of sample count rate was made on the basis of this evidence.

Effect of merthiolate fixation on sample activity experiments indicate that loss of activity occurs non-linearly for approximately the first eight hours (Figure 94). Approximately 14 percent loss occurs during the first four hours, another five to seven percent during eight additional hours. On the average, approximately 21

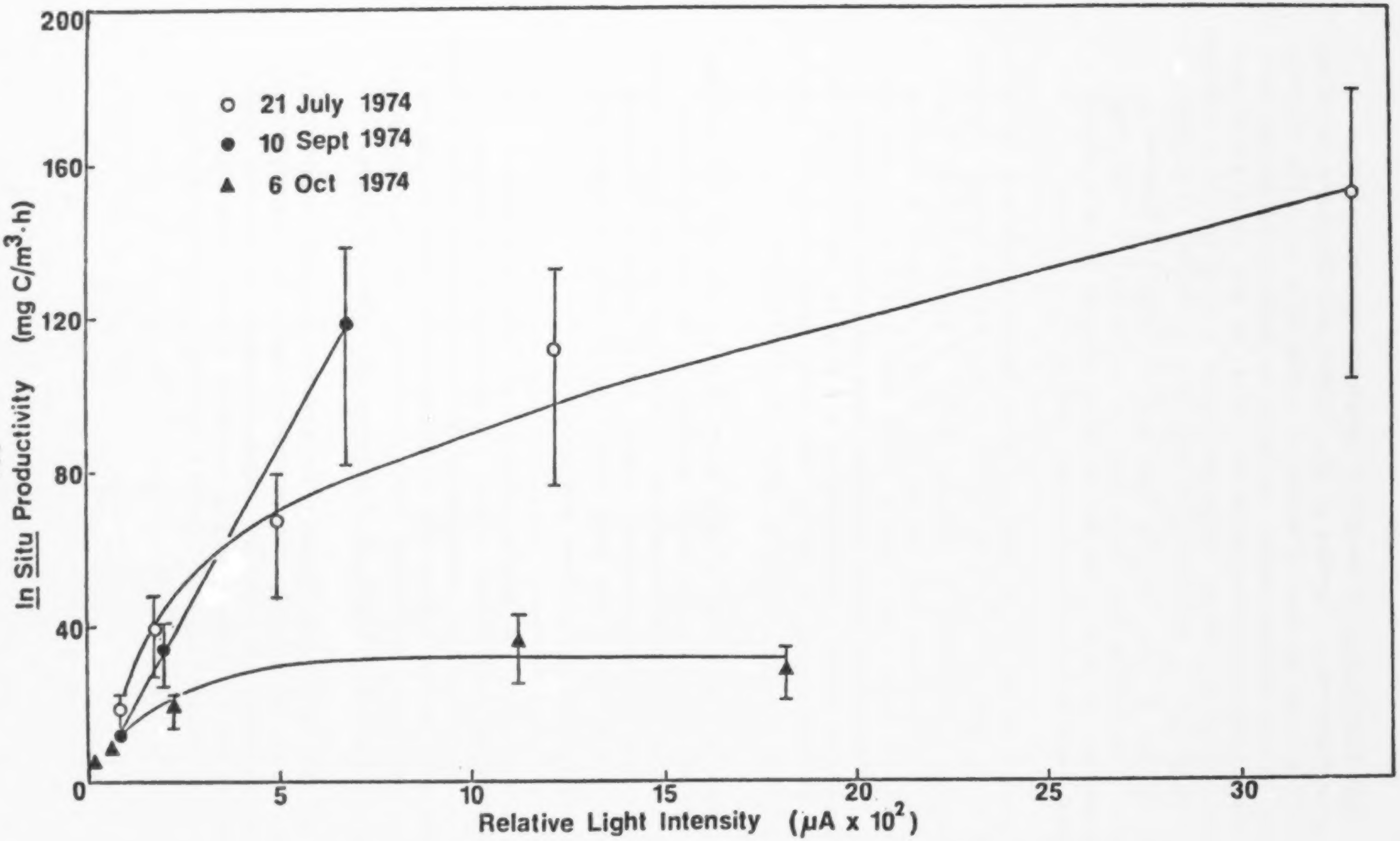

Figure 91. Relationship of in situ productivity to relative light intensity near Rattlesnake Island.

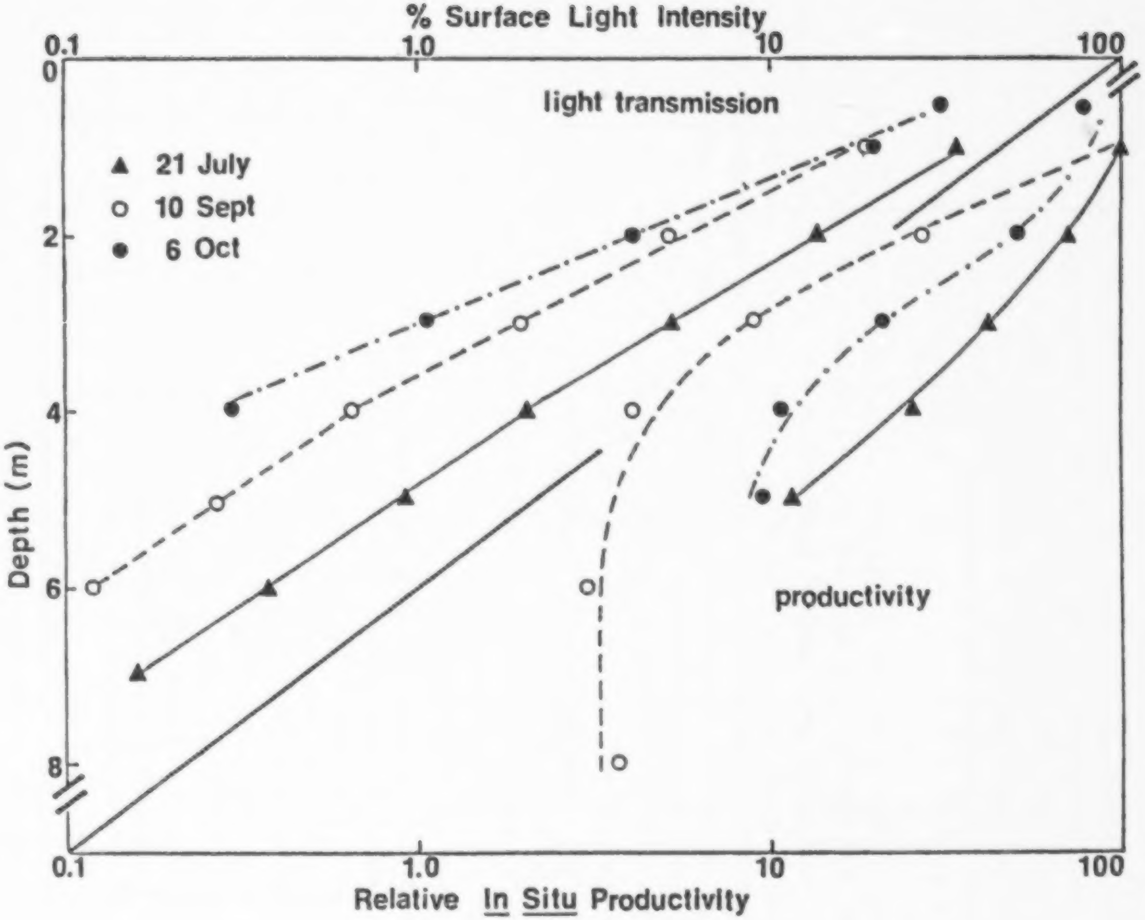

Figure 92. Relationship of relative in situ productivity and light transmission of depth near Rattlesnake Island.

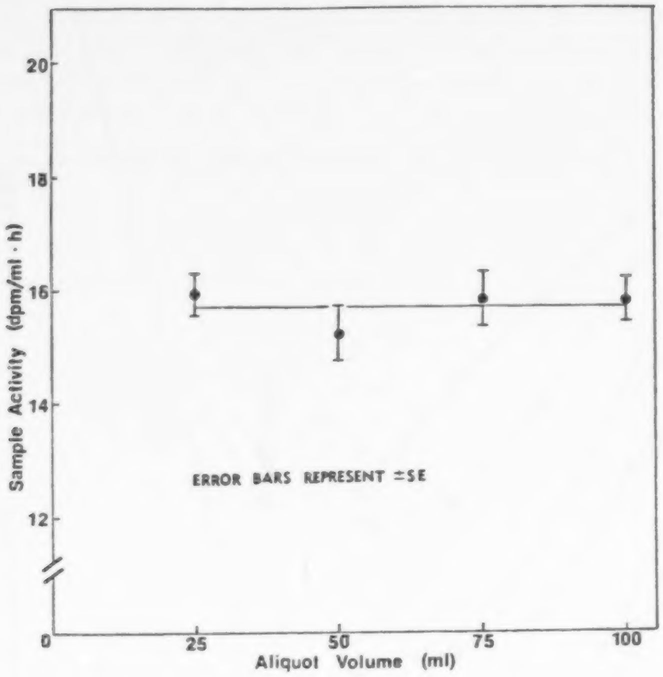

Figure 93. Relationship of sample activity to aliquot volume.

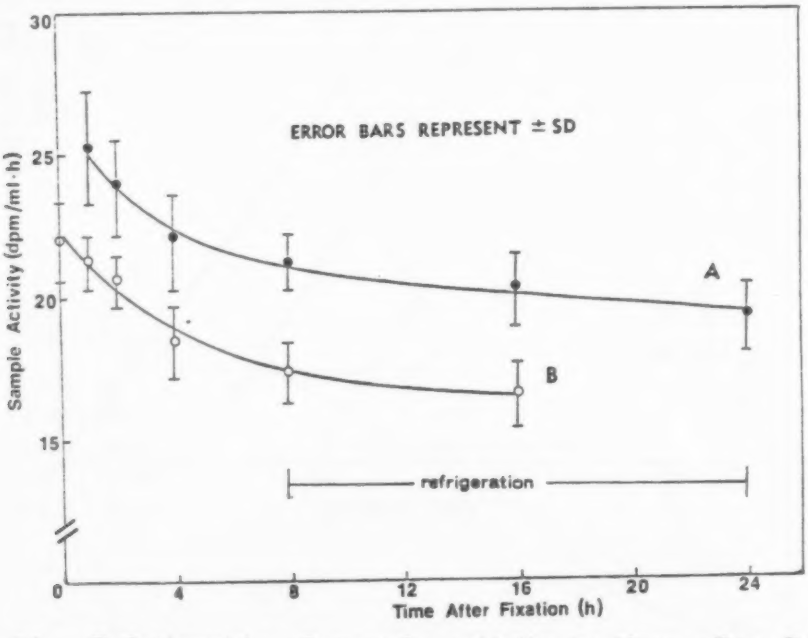

Figure 94. Relationship of sample activity to time after fixation.

percent of the original activity is lost per sample within eight hours after fixation. Again individual bottles vary in loss rates. Hourly loss rates become similar after eight hours.

Relative incubator light intensity in clear water averaged 900 μ A (range of 775-1075 μA) and 775 μ A (range of 675-975 μA) in turbid water. When the clear plexiglass top covered the top of the incubator during rough weather, relative light intensity in clear water was reduced from 900 to 825 μ A (range of 725-925 μA), a reduction of 9 percent. Since no records were kept of the horizontal position of the bottles in the incubator, no correction was applied to the carbon assimilation rates.

The estimated average range of total error of a single productivity measurement determined by the methodology presented in this report is +18 percent to -32 percent. Counting statistics, syringe calibration, ampule activity calibration and fixation effects were factors considered. Dark bottle ^{14}C uptake and light bottle ^{14}C uptake can both be expressed in relative units in which light bottle uptake equals 100 and dark bottle uptake its corresponding percentage. From such consideration the relative dark uptake (49 percent) that yields the greatest uncertainty to the net sample count rate contributes a total probable error in counting statistics of 10 percent ($P = 0.05$). Mean relative dark bottle uptake of 14 percent ($n = 182$) yields a probable error of 3 percent ($P = 0.05$), and thus the mean probable error caused by counting statistics alone is ±3 percent. Syringe accuracy contributed ±5 percent error. Accuracy of ampule calibration by New England Nuclear Corp. as determined by ampule lables and technical information is assumed to be ±10 percent of the stated value of 5.0 μCi per 5.0 ml [1.0 μCi/1.0 ml] aqueous solution. Samples were assumed to have been filtered within four hours after fixation. Therefore, samples lost 14 percent of their original activity (Figure 94, curve B). This estimate is probably conservative since filtration of some samples was not completed for at least 24 hours. No accurate records were kept of the time between sample fixation and filtration, as the fixation effect was not discovered until about two-thirds of the samples had been taken through the sampling season. For this reason primary productivity measurements remain uncorrected for sample activity loss. The fixation effect contributes the greatest uncertainty to the methodology used during this study.

Agreement between duplicate light bottles (n = 183 pairs) averaged 21 percent ±2 percent (SE) for all samples over the entire season. This measured value falls within the predicted range of +18 percent to -32 percent. Saunders et al. (1962) reported that ±20 percent is the normally accepted error for estimates of photosynthesis. The positive side of the estimated error for 1974 is 10 percent less than Saunders' figure, while the negative side is 60 percent greater, since sample fixation causes loss in addition to the three other sources of error considered. The amount of error introduced by the relationship of Glooschenko et al. (1974) is unknown. Error bars in figures accompanying the text represent the estimated error of +18 percent to -32 percent unless otherwise indicated.

Graphs of the vertical distribution of incubator productivity within the euphotic zone reveal that the wide range of error may reduce productivity maxima and minima of raw data. For example, the graph of incubator productivity vs. depth for Station 47 on 30 July (Figure 95) shows that peaks at 1 m, 5 m, and 14 m reduce to a small increase (approximately 20 percent) from 1 m to a plateau at about 7 m. Superficially, a doubling of incubator productivity is observed from 2 m to 5 m and from 7 m to 14 m. Vertical profiles where maximum productivity was ≥ 1.32 times the minimum productivity were compared. Maximum to minimum productivity ratios ≥ 1.32 were considered significant, since -32 percent was the average maximum error involved in making the productivity estimates. The number of significant productivity profiles was 15 of 39 or 38 percent of the total incubator productivity experiments.

Central Lake Erie incubator productivity profiles had a wider range of carbon fixation rates than western Lake Erie profiles. Maximum productivity to minimum productivity ratios for central Lake Erie averaged 1.80, 1.83, and 1.17 for early August, mid-August, and late October, respectively. Western Lake Erie ratios averaged 1.33, 1.16, and 1.07 for late July, early September, and late October, respectively. For central Lake Erie at Station 23 during both mid-August and late October maximum productivity at 1 m decreases with depth (Figure 95). The profile at Station 25 in mid-August showed increasing productivity from about 5 m to a plateau at 15 m to the bottom of the euphotic zone at 18 m (Figure

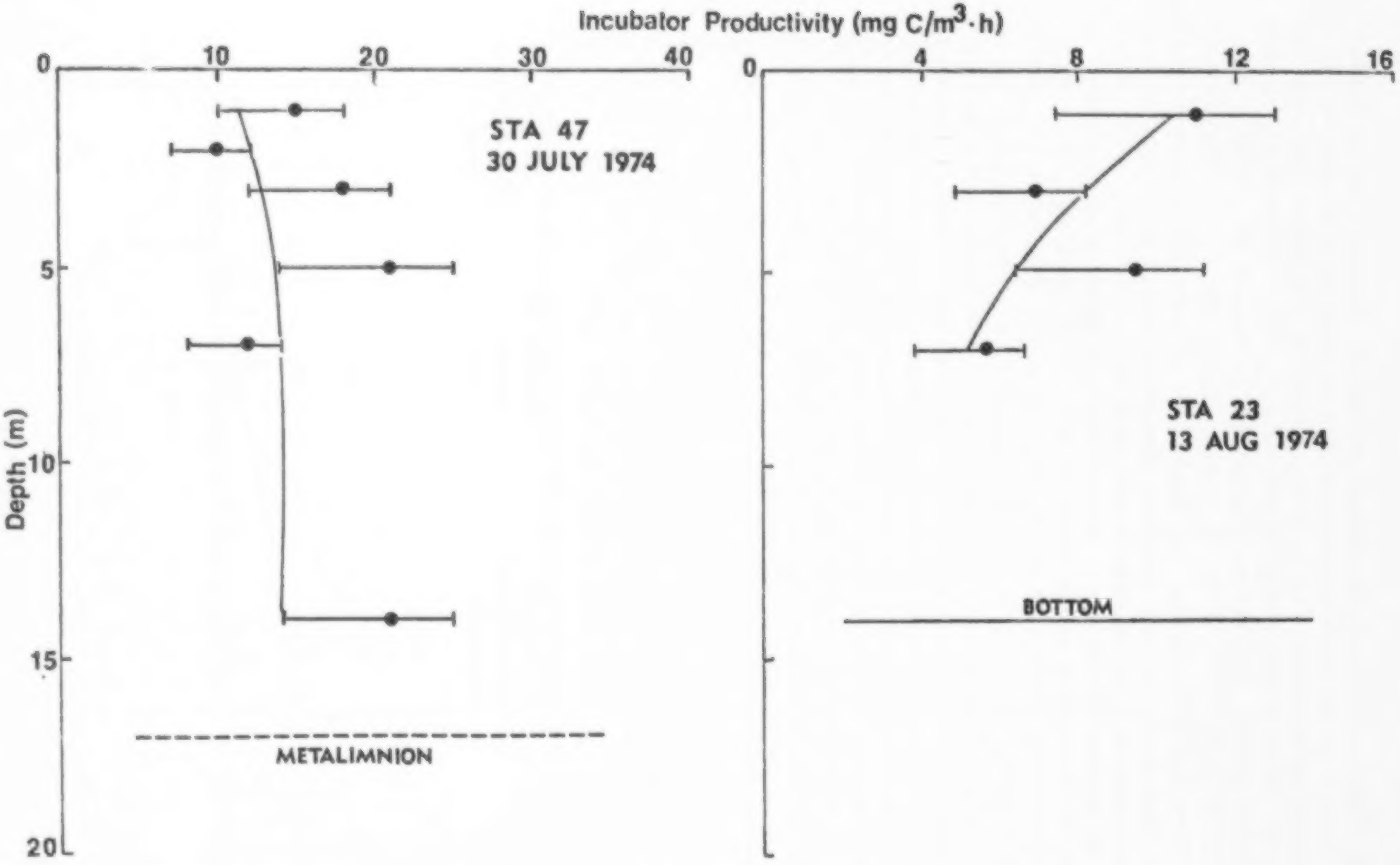

Figure 95. Vertical profile of incubator productivity at station 47 on 30 July 1974 and station 23 on 13 August 1974.

96). For Station 30 in early August incubator productivity increased linearly from 1 m to 11.5 m (Figure 96); in mid-August productivity remained the same from 1 m to 4 m, where it increased and reached a plateau at 15 m in the metalimnion (Figure 97). Station 34 in mid-August had a profile similar to Station 30 in Figure 97 although the euphotic zone extended to only 11 mm. Station 36 in mid-August had a nearly linear profile sinilar to Station 30 (Figure 96) except it started at 3 m. Station 39 on late October had minimum productivity at 5 m which increased at 7 m to nearly the level at 1 m (Figure 97). Productivity at Station 48 in early August had a maximum at 4 m and decreased to nearly the same level as at 1 m (Figure 98); in mid-August productivity remained nearly the same for the first five meters, increased slightly at 9 m, and it decreased to a minimum level at 13 m (Figure 98). Productivity at Station 52 in late July had a sharply defined maximum at 3 m (Figure 99). In mid-lake areas phytoplankton accumulated in the lower epilimnion and metalimnion. Station 30 (Figures 96 and 97) showed this trend in incubator productivity profiles. The profile for 14 August is supported by chlorophyll a (uncorrected) data (Table 66). Productivity at Station 36 on 15 August showed a marked increase toward the metalimnion. However, chlorophyll a concentration and productivity do not agree.

TABLE 66. VERTICAL DISTRIBUTION OF UNCORRECTED CHLOROPHYLL a CONCENTRATION AT STATIONS 30 AND 36 IN AUGUST 1974

Station 30 Depth (m)	14 August Concentration (mg/m^3)	Station 36 Depth (m)	15 August Concentration (mg/m^3)
1	2.7	1	3.9
14	3.9	16	3.9
16	3.8	19	3.6
20	3.5	23	5.5

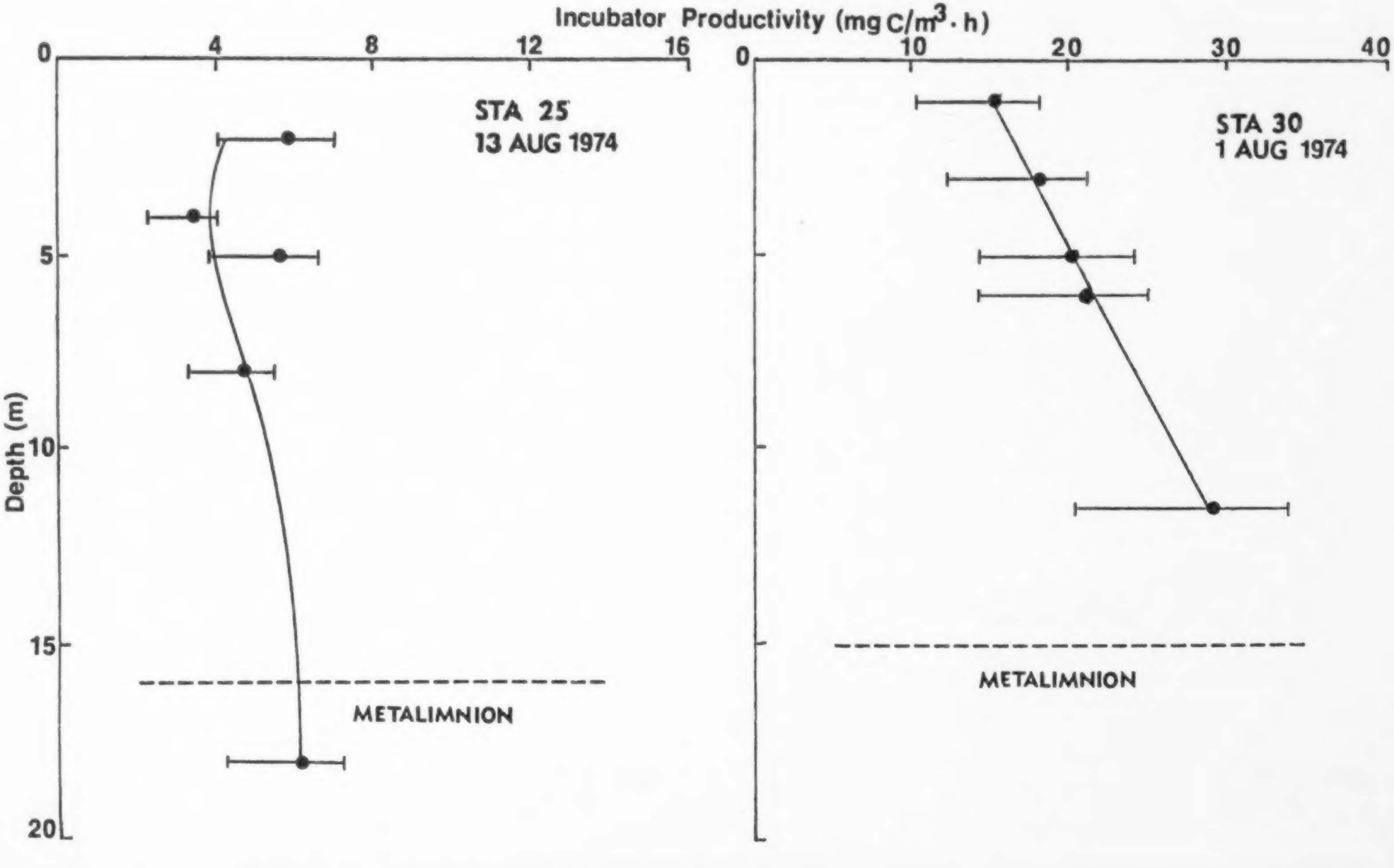

Figure 96. Vertical profile of incubator productivity at station 25 on 13 August 1974 and station 30 on 1 August 1974.

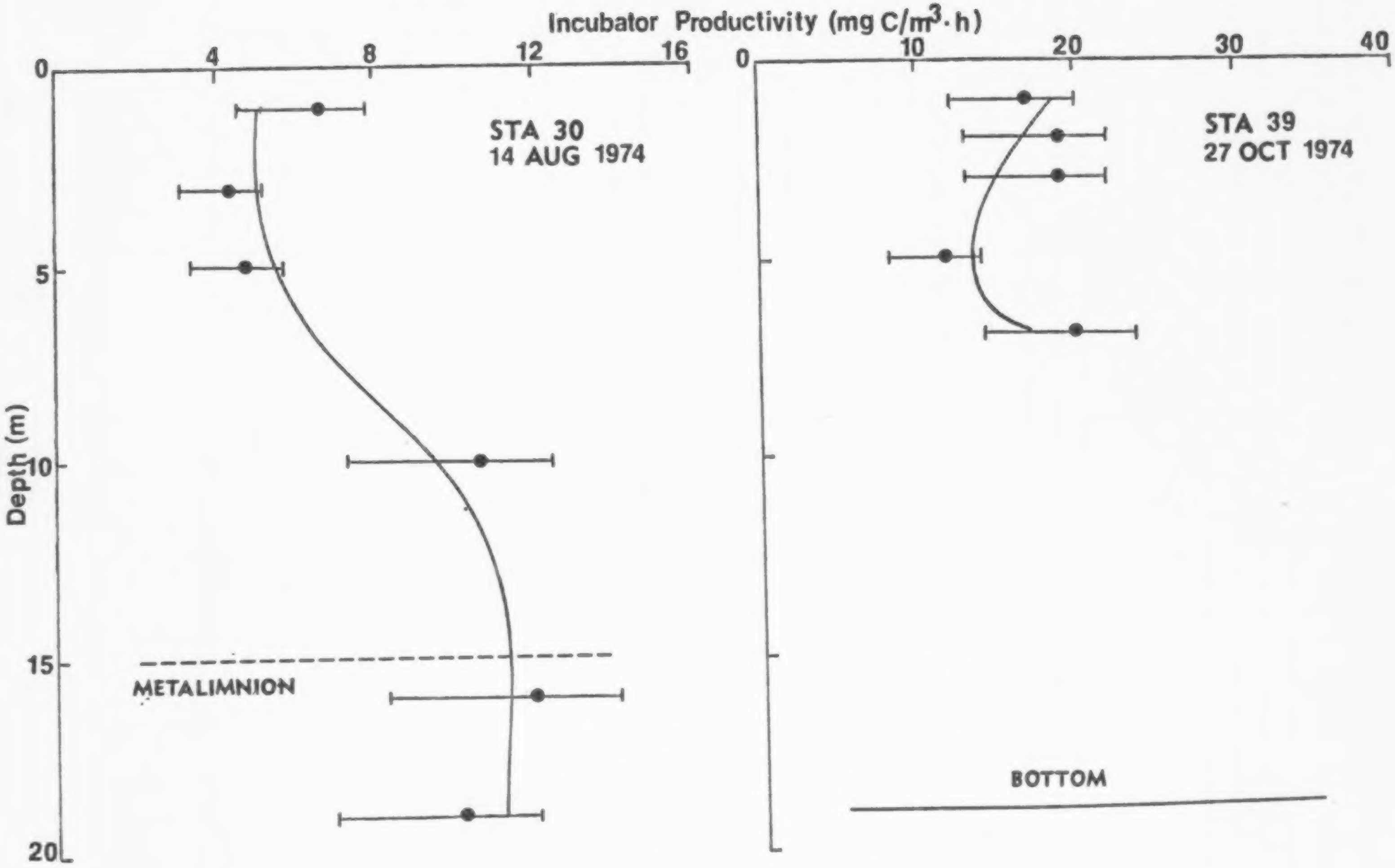

Figure 97. Vertical profile of incubator productivity at station 30 on 14 August 1974 and station 39 on 27 October 1974.

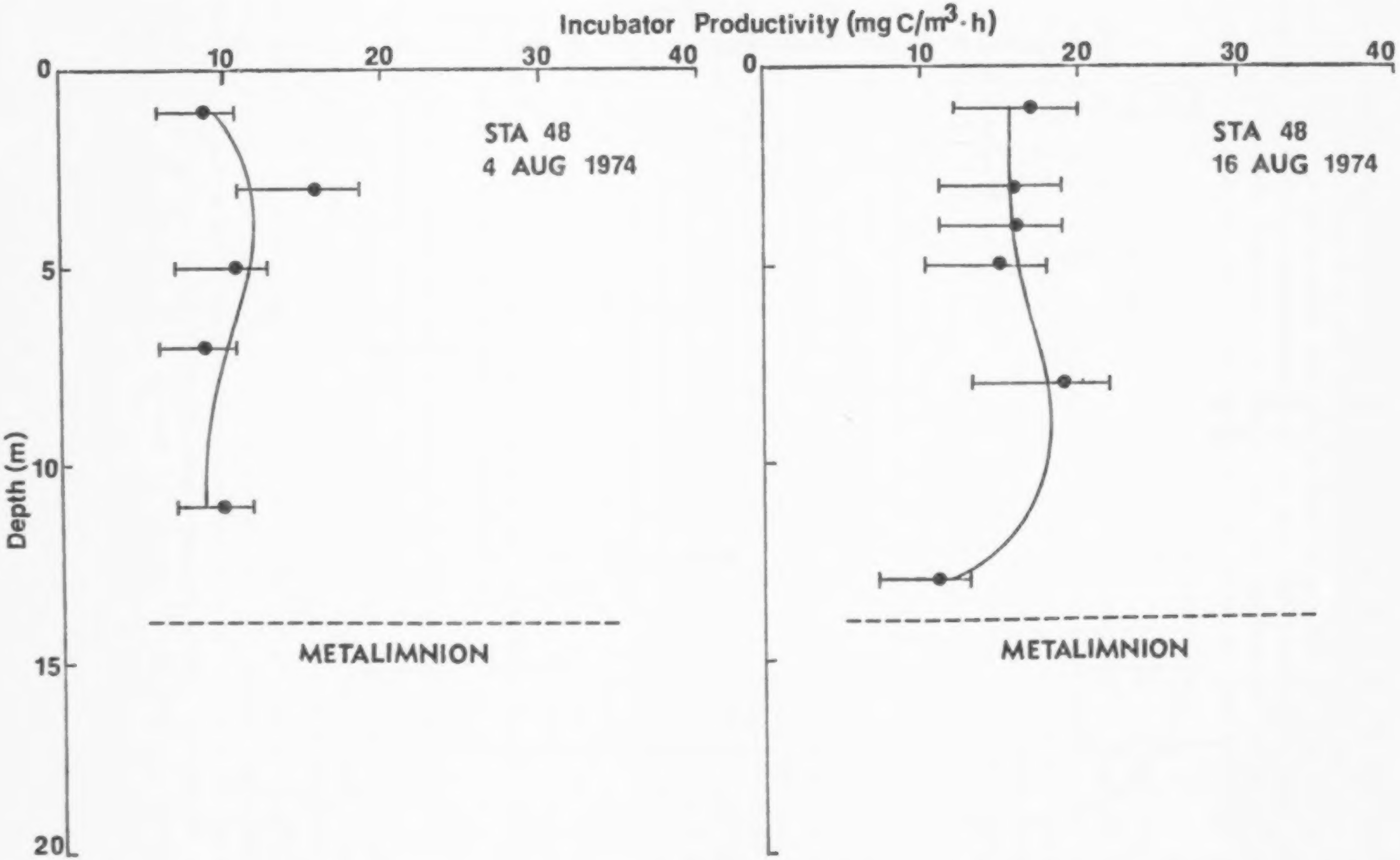

Figure 98. Vertical profile of incubator productivity at station 48 on 4 August 1974 and 16 August 1974.

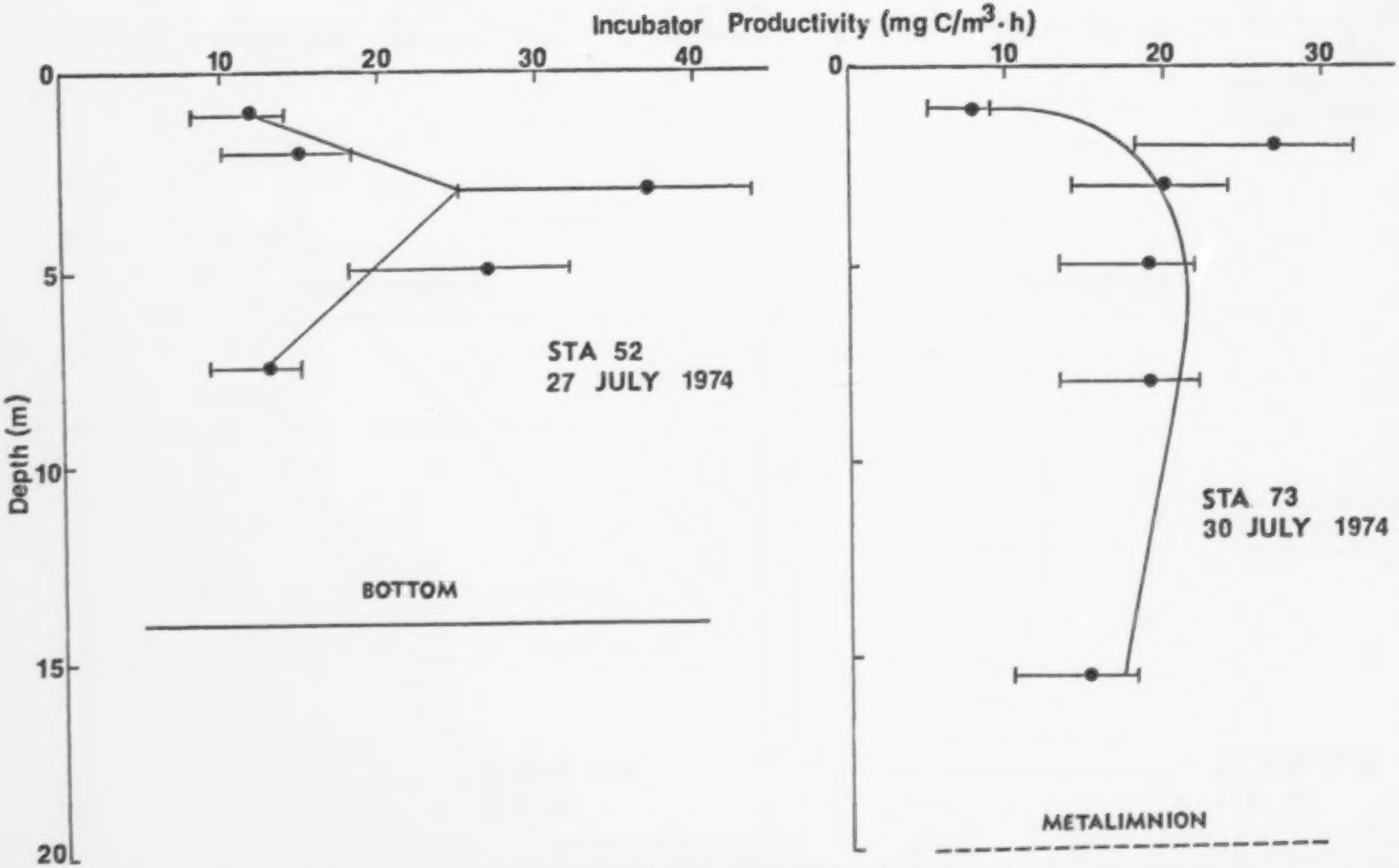

Figure 99. Vertical profile of incubator productivity at station 52 on 27 July 1974 and station 73 on 30 July 1974.

In western Lake Erie productivity increased linearly with depth at Station 61 in late July similar to Station 30 in Figure 96. Productivity at Station 66 in late July had a profile similar to Station 52 (Figure 99) with a maximum at 5 m, but the maximum was not quite as sharply defined. Productivity at Station 75 in early September resembled Station 30 (Figure 96) although the increase was not quite linear.

Central Lake Erie showed higher relative dark bottle ^{14}C uptake (dark bottle activity) than western Lake Erie. Central basin mean dark uptake increased during thermal stratification from 18 percent in early August to 24 percent in mid-August and decreased after fall overturn to 12 percent in late October. Relative dark uptake ranged from 3-34 percent and 3-58 percent for early and mid-August, respectively. Relative dark uptake of 560 percent and 630 percent at Station 23 on 13 August and 77 percent at Station 73 on 30 July is considered aberrant and unexplainable. Western Lake Erie relative dark uptake remained at the same levels throughout the season, as mean rates were 6 percent, 8 percent, and 7 percent (excluding Station 61) for late July, early September, and late October, respectively. The mean relative dark uptake for all samples during the season was 14 percent. For incubator studies in the eastern tropical Pacific Ocean, Jones et al. (1953) reported relative dark ^{14}C uptake of 16-22 percent for productivity experiments lasting four to eight hours. Larson (1972) reported relative dark uptake from 4-70 percent during in situ productivity studies in Crater Lake. Relative dark ^{14}C uptake of 6 percent has been obtained in western Lake Erie (Verduin, personal communication); the western basin value found in 1974 agree with this estimate. Obviously, higher relative dark uptake drastically reduces light bottle uptake when corrected by subtraction.

Primary productivity at one meter in central and western Lake Erie during 1974 showed high correlation ($r = 0.92$) with uncorrected chlorophyll a concentration, which is a phytoplankton biomass indicator (Figure 100). The correlation exceeds by three-fourths that one reported by Glooschenko et al. (1974) for mean values per cruise of chlorophyll a and incubator productivity in surface water in all three basins. Glooschenko et al. called the slope of the graph the assimilation number, the units of which are mg C/mg chlorophyll a·h. Glooschenko's mean assimilation number of 1.93 mg C/mg chlorophyll a·h agreed to within 10 percent of that for 1974.

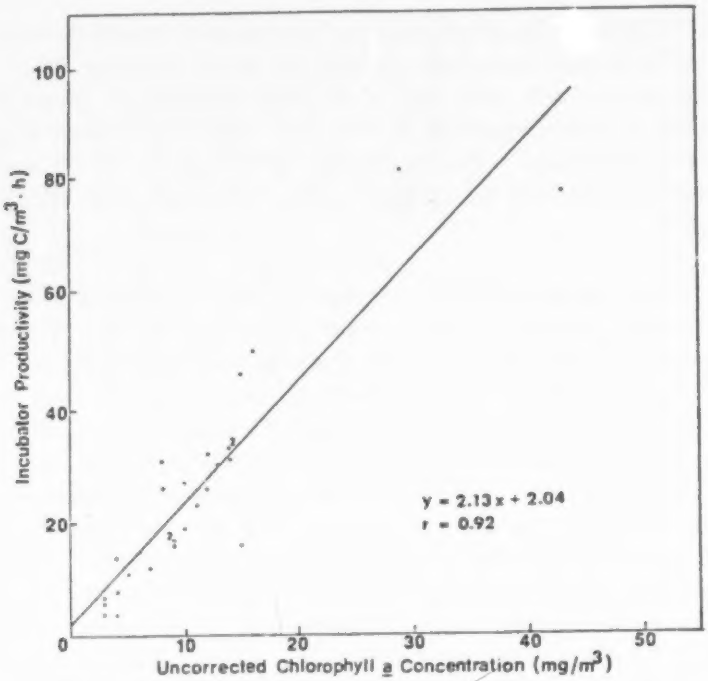

Figure 100. Relationship of incubator productivity to uncorrected chlorophyll *a* concentration at 1 M depth.

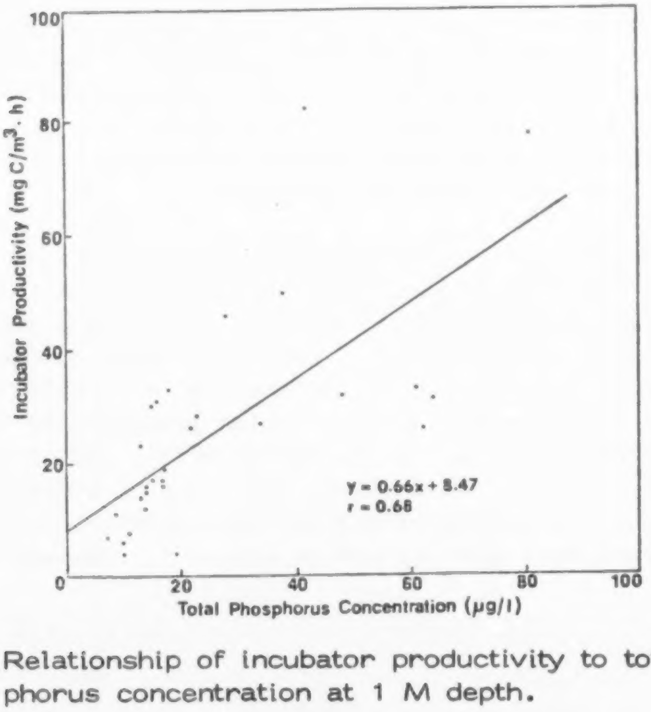

Figure 101. Relationship of incubator productivity to total phosphorus concentration at 1 M depth.

The relationship between incubator primary productivity and nutrient concentration in central and western Lake Erie during 1974 is not clear. From the concentrations of total and soluble reactive phosphorus and total inorganic ammonia, and nitrate-nitrite nitrogen in the two basins, only total phosphorus correlated with incubator productivity ($r = 0.68$) for lake water samples from the one meter depth (Figure 101). Brydges (1971) found that in western Lake Erie station averages of chloropyll a from a composite sample of 1.5 m and 7.5 m water were positively correlated with total phosphorus at 1.5 m for the years 1967-1969. Megard (1972) reported that for eutrophic Lake Minnetonka, Minnesota total phosphorus in the range of 0-170 mg/m^3 (μg/1) was linearly correlated with daily maximum photosynthesis per unit volume of water during the months of July, August, September. Brydges (1971) also found that soluble phosphorus, nitrate-nitrite nitrogen, and ammonia nitrogen did not correlate with chlorophyll a.

Light energy penetrating the surface waters in central Lake Erie was transmitted more readily than in western Lake Erie during thermal stratification in August (Table 67). The mean euphotic zone in central Lake Erie was 2.4 times deeper than in western Lake Erie. In mid-August light transmission improved slightly. Upon lake overturn the euphotic zone in central Lake Erie was only 30 percent deeper than in western Lake Erie. Verduin (1954) reported that dissolved pigments have not been observed in western Lake Erie, and that differences in light transmission were attributable to suspended particles. The same is assumed for central Lake Erie.

Incubator productivity represents maximal carbon assimilation rates that result from optimal light intensities. A rough approximation of incubator light intensity assumes that full light intensity measured by the photometer (10.5 mA) equals 10,000 foot candles (Saunders et al. 1962) during the brightest days. Therefore, since an average of 0.9 μamps of relative light intensity reaches the tops of the bottles in the incubator under clear water conditions, approximate light intensity is 9000 lux. Talling (1966) stated that the light-saturating range of Asterionella communities in English lakes is 8000-10,000 lux. Talling (1966), using an incubator equipped with daylight fluorescent lamps, converted incubator light intensity to quantity of photosynthetically active radiant energy (400-700 nm) by the conversion factor of 4.1 kerg/cm^2 per sec per kilolux. Therefore, 37 kerg/cm^2 per sec (9×4.1) approximates the radiant energy received by phytoplankton samples in the incubator during the 1974 study. If the areal and time units are changed to m^2 and h, respectively, the resulting radiant

TABLE 67. MEAN SECCHI DISC AND EUPHOTIC ZONE DEPTHS FOR CENTRAL AND WESTERN LAKE ERIE FROM JULY-OCTOBER 1974

No. of Stations	Basins	Secchi disc (m)	Euphotic Zone (m)
Cruise 6			
5	central	4.5	12.0
5	western	2.0	5.0
Cruise 7			
8	central	6.0	14.5
Cruise 8			
4	western	1.0	3.5
Cruise 10			
11	central	3.0	8.0
5	western	2.0	6.0

energy of approximately 1 × 10^{12} erg/m^2 per hour falls near the maximum carbon uptake rates on the light-saturated portions of photosynthesis-light intensity curves published by Stadelmann, et al. (1974) for Lake Ontario phytoplankton communities.

Photosynthetic productivity per unit volume of water reflects phytoplankton densities in the water column at a particular depth, but the relationship is not a simple one to one correspondence. Talling (1966) found for English lakes a broad correlation from April to June between population density (cell number) and gross photosynthetic rate per unit volume of water. Blelham Tarn had population densities and photosynthetic rates two to three times greater than Windermere North Basin. In both lakes phytoplankton from below the surface showed greater population densities and greater photosynthetic rates than surface phytoplankton. Verduin (1960) found that a five-fold increase in population density accompanied a doubling of net photosynthetic rate per volume of water, when the phytoplankton community changed from June to August, 1957. An explanation may lie in the specific photosynthetic rate of the phytoplankton. Megard (1972) defined the specific photosynthetic rate $\frac{\text{mg C/m}^3\cdot\text{day}}{\text{mg chlor }\underline{a}\text{/m}^3}$, which is the equivalent of the assimilation ratio when calculated per hour. Talling (1966) used both cholrophyll *a* and cell number per unit volume of water as measures of population density, and Verduin (1960) used phytoplankton volume per unit volume of water. Specific photosynthetic rate decreased with increasing depth during *in situ* productivity studies on Lake Tahoe (Kiefer et al. 1972). The 1974 incubator studies reveal that at the same light intensity at Station 47 on 12 August the 1-m and 13.5-m samples yielded specific photosynthetic rates of 2.5 and 3.7 mg C/mg chlor *a*·h, respectively. This increase of 48 percent resulted from a 15 percent increase in the incubator productivity from 13 to 15 mg C/m^3·h and a 22 percent decrease in chlorophyll *a* concentration from 5.2 to 4.0 mg chlorophyll *a*/m^3 at 13.5 m. Talling (1966) found that the light-saturated gross specific photosynthesis of *Asterionella* populations increased during periods of population decline, and higher specific photosynthesis was found at times of lower cell concentration and active cell division. Another complication is that net specific photosynthesis per unit volume of phytoplankton increases with decreasing phytoplankton volume per liter of water (Verduin 1960). Rodhe (1958) used ^{14}C to find that nannoplankton contributed a greater share of the primary productivity per standing crop of phytoplankton than did netplankton. Primary productivity per unit volume of water is the product of the specific photosynthetic rate $\frac{\text{mg C/m}^3\cdot\text{h}}{\text{mg chlor }\underline{a}\text{/m}^3}$, and the phytoplankton density (mg chlor *a*/m^3, Megard, 1972). For these reasons incubator productivity is a metabolic index of population density as Saunders et al. (1962) believed when they exposed samples from different depths to a light intensity of 500 foot candles. The strong correlation between incubator productivity and chlorophyll *a* concentration at the one meter depth in 1974 emphasizes their contention.

Both incubator and *in situ* productivity data for 1974 remain uncorrected for excretion of organic matter, respiration losses, and grazing because they were not quantified by experiment. Excretion of organic compounds may cause significant underestimates of productivity. Fogg et al. (1965) found that during a four-hour experiment approximately 34 percent of the initially assimilated ^{14}C was excreted by diatom dominated communities in English lakes. With the ^{14}C technique no way exists to measure loss of $^{14}CO_2$ during breakdown of organic compounds in respiration (Kiefer et al. 1972). The reaction involved is:

$$^{*}CH_2O + O_2 \longrightarrow {}^{*}CO_2 + H_2O.$$

Significant grazing of phytoplankton standing crop may reduce productivity. Parkos et al. (1969) felt that grazing may be important in localized areas of lakes but should not cause the large variations in productivity they observed in each of the four Great Lakes they investigated. Verduin (1952) felt that grazing was insignificant in western Lake Erie. Glooschenko et al. (1974) felt that the zooplankton in Lake Erie, which are characterized by protozoans, rotifers, and cladocerans, consume detritus and bacteria more than phytoplankton.

For the 1974 incubator studies ^{14}C uptake was assumed to be linear at constant light intensities. The literature gives varying results. Barnett and Hirota (1967) found that at constant light intensity the rate of ^{14}C uptake was constant during a two-hour incubation. In a second experiment of four hours duration, Barnett and Hirota used phytoplankton concentrations ten times greater, and light intensity was half of the first experiment. They found that ^{14}C uptake rate decreased to 62 percent of the rate at one hour.

Fogg et al. (1965) found that photosynthesis was proportional to incubation time under constant light intensity *in situ* and in the laboratory, but organic matter was excreted at an almost constant percentage of the photosynthetic uptake.

Extracellular ^{14}C adsorbed to phytoplankton leads to overestimates of productivity. McMahon (1973) showed that rinsing filters with 100 ml of distilled or filtered lake water removed extracellular ^{14}C, which had led to erroneous conclusions concerning self-absorption. The investigator assumed that the acid and filtered lake water rinses used in 1974 adequately removed extracellular ^{14}C.

Estimation of phytoplankton productivity at several stations during different times of the day may exaggerate productivity relative to each other. Vollenweider and Nauwerck (1961) found during in situ studies on Lake Erken, Sweden the interval of 0530-0930 yielded productivity per unit area of water one third of the daily total of a series of five four-hour time blocks. Holmes and Haxo (1958) demonstrated changes in photosynthesis throughout the day in incubator studies at a station in the tropical eastern Pacific Ocean. Maximim photosynthesis occurred at 0800-1000. Verduin (1957) found that the period 0700-1000 in western Lake Erie yielded maximal net photosynthetic rate per unit volume of water two-thirds greater than during the intervals 1000-1300 and 1300-1600. All times are given in EST.

Whether the ^{14}C method estimates net or gross productivity remains unsolved. Saunders (1964) felt that because the sum of a series of short experiments over a day exceeded the estimate of a single full day exposure, the series estimated gross productivity and the single exposure net. Vollenweider and Nauwerck (1961) suggested that productivity measured by ^{14}C lies between net and gross.

Both incubator and in situ productivity estimates made by the ^{14}C method include combined contributions by phytoplankton and bacteria. Cody (1972) states that the measurement of carbon assimilation is complicated by autotrophic bacteria, both chemosynthetic (aerobic) and photosynthetic (nonsulfur which are aerobic and sulfur which are anaerobic). The relative amount of bacterial assimilation is unknown.

Phytoplankton, zooplankton, and bacteria all play a role in dark ^{14}C uptake (Gerletti 1968). Sorokin (1965) described three groups of bacteria involved in aerobic decomposition of organic matter which account for the major part of dark CO_2 assimilation in surface layers of eutrophic and mesoeutrophic lakes. Another group of bacteria intermediate between heterotrophic and chemosynthetic oxidizes simple organic products of anaerobic decomposition. A third group are chemoautotrophs that utilize CO_2 in the syntheses of all their organic compounds.

During in situ studies on Lake Maggiore, Italy, Gerletti (1968) found that below the optimal level of illumination (where maximum photosynthesis is expected to occur) relative dark uptake of $^{14}CO_2$ (dark bottle activity expressed as percent of the corresponding light bottle activity) increased. In situ experiments at Rattlesnake Island during 1974 support Gerletti. Relative dark ^{14}C uptake on 21 July was 2 percent at one meter, increasing to 14 percent at five meters; for 10 September, 2 percent at one meter, increasing to 33 percent at six and eight meters; and on 6 October, 6 percent increasing to 35 percent at four meters. However, in the incubator studies at an optimal light intensity, relative dark bottle rates ranged from 1-58 percent and were especially high in the central basin during late July to mid-August. On the hottest summer days incubator temperature remained within 2°C of the lake surface temperature. Since the temperature from surface to lower epilimnion did not vary by more than 2°C on the average over the sampling season, the temperature differential between incubator and sample depth is negligible. Even though light intensity in the incubator is optimal, a significant increase in relative dark bottle activity occurs. The source of this uptake is not specifically known, although the bottle surface effect on bacteria may stimulate their growth (Gerletti 1968). Menon et al. (1972) reported bacterial densities of 3.3-3700 × 10^3/ml and 3.4-790 × 10^4/ml for central and western Lake Erie, respectively. Vertical distribution was uniform until stratification, when hypolimnion bacterial densities increased more than epilimnion densities. Bacteria in late August utilized organic matter from excretion and degradation products of blue-green and green algal blooms to attain maximum densities.

Morris et al. (1971) found that with marine phytoplankton relative dark uptake of ^{14}C became greater with smaller population densities. Smaller phytoplankton densities in both central and western Lake Erie in 1974 yielded higher relative dark uptake, but the relationship is non-linear (Figure 102). Relative

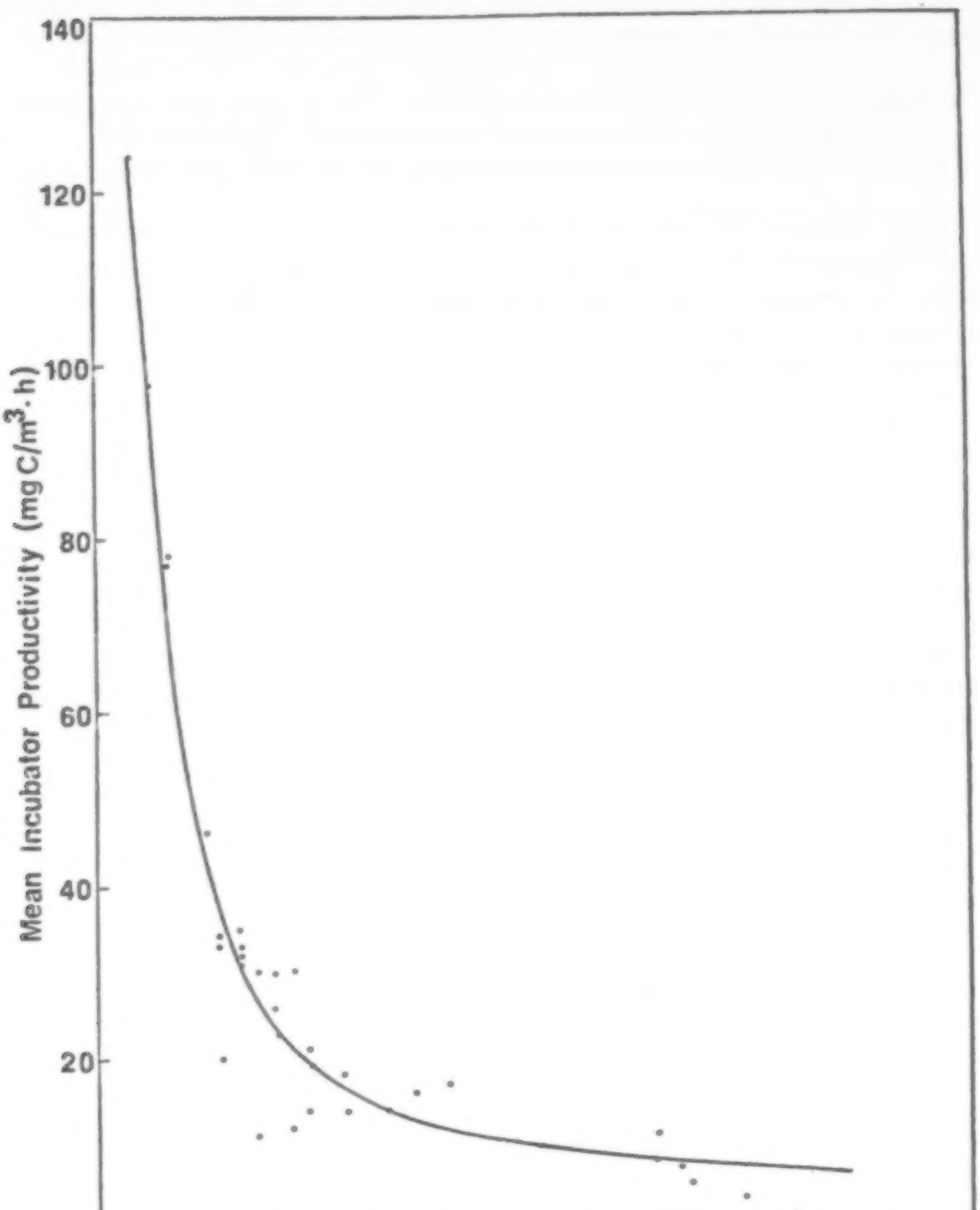

Figure 102. Relationship of mean relative dark ^{14}C uptake to mean incubator productivity at each station in central and western Lake Erie.

dark uptake increased with decreasing turbidity (Figure 103), which supports the previous relation.

No relationship was noted between dark ^{14}C uptake and temperature. For both relative and absolute values equally high and low rates were observed at temperature ranges of 10-13°C and 18-24°C.

In situ productivity vs. depth profiles show the effect of decreasing light intensities on carbon assimilation rates, whereas incubator productivity profiles at constant light intensity show relatively little change in carbon assimilation rates. The shipboard counterpart to Rattlesnake Island, Station 67, did not have significant changes in vertical distribution of productivity. *In situ* profiles show that productivity at one meter and deeper closely parallels light transmission in all three experiments down to a relative light intensity of approximately 10 percent of the surface light intensity. Such parallelism indicates that phytoplankton populations are homogeneously distributed, at least down to the level of 10 percent of the surface light intensity. Rodhe (1965) found that the slopes of assimilation curves of nine lakes closely agreed with the slope of the most penetrating component (usually green) of subaquatic light at a level from 1-12.5 percent of the subsurface intensity of the component.

Incubator data showed that the phytoplankton in both basins survived the light intensity of the water bath. For example, a sample of lake water from four meters at Station 53 on 6 September from a relative light intensity (775 μA) had a productivity potential nearly 20 percent greater than a sample from one meter, which received about a 370 times greater relative light intensity. This suggests that the water at Station 53 circulates completely down to four meters so that the cells at four meters do not remain in total darkness, otherwise they may have been injured by the incubator light intensity and would not have functioned photosynthetically, or if so, then at a reduced rate. Water temperature and oxygen concentration remain unchanged from one meter to four meters which supports this hypothesis. Keifer et al. (1972) reported that phytoplankton from 100-400 m in Lake Tahoe survived light intensity increases of 10^7, as When the samples were incubated at a light intensity 40 percent of the surface, they had photosynthetic potentials per unit of chlorophyll *a* slightly less than phytoplankton at 75 m in the euphotic zone (85).

The incubator productivity-total phosphorus relationship

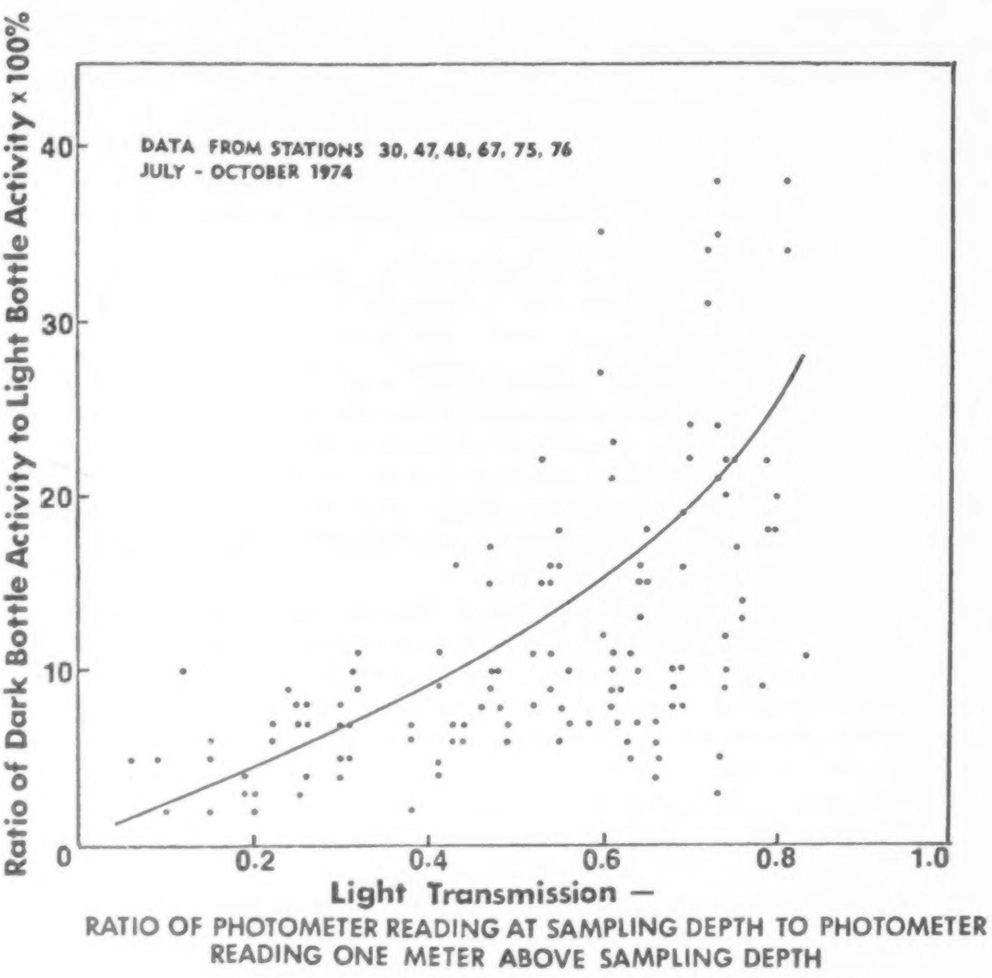

Figure 103. Relationship of relative dark ^{14}C uptake to light transmission.

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may indicate that total phosphorus is an indicator of phytoplankton densities. Brydges (1971) suggested that if total phosphorus concentrations were reduced, there would be less algae. The 1974 incubator data support Brydges' argument.

The parellelism in the in situ productivity-light transmission curves in Figure 92 suggests that light is a controlling factor in primary productivity in western Lake Erie. Since total phosphorus concentration is lenearly related to incubator productivity at the one-meter depth, then both light and total phosphorus may together limit primary productivity. If the light-in situ productivity relationship holds for central Lake Erie, then both factors may be limiting in central Lake Erie also.

SUMMARY

Western basin incubator productivity was 3.5 times greater than central basin incubator productivity in the summer and 1.5 times greater in the fall. Incubator productivity estimates were comparable to those in 1970. Central basin incubator productivity decreased in late summer and increased upon fall overturn. Western basin incubator productivity declined throughout the season.

In situ productivity-light intensity curves for western Lake Erie showed that phytoplankton are photosynthetically active at lower light intensities in October, as opposed to July and September, and that maximal productivity is reached within a narrower range of light intensities. Maximum productivity occurs at approximately one meter. In all three in situ experiments relative productivity curves lay parallel to light transmission curves down to a level of approximately ten percent of the surface light intensity.

Estimated errors for the 1974 methodology showed that a slightly greater total error existed than was normally accepted in other studies cited. Each sample lost an average of 14 percent of its initially assimilated ^{14}C when merthiolate fixative was used. This fixation effect had the greatest uncertainty in the estimate of total error.

Incubator productivity profiles showed several forms. Maxima were located at one meter, slightly below one meter, and some mid-lake central basin profiles increased toward the metalimnion. Lower maximum to minimum incubator productivity ratios indicate that western Lake Erie waters are mixed more thoroughly than central Lake Erie waters.

Central basin relative dark bottle ^{14}C uptake averaged three times greater than western basin relative dark bottle uptake. Central basin relative dark bottle uptake increased during thermal stratification, yet western basin relative dark bottle uptake remained rather constant. Higher relative dark bottle uptake occurred in areas of less turbidity and phytoplankton densities. The effect of temperature on relative dark bottle uptake was not evidenced.

Incubator productivity correlated with uncorrected chlorophyll a concentration and total phosphorus concentration at the one meter depth. The incubator productivity-total phosphorus, and relative in situ productivity-light transmission relationships suggest that light and phosphorus together operate as limiting factors in central and western Lake Erie.

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SECTION 9

ZOOPLANKTON DISTRIBUTION IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

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Center for Lake Erie Area Research
The Ohio State University

INTRODUCTION

Zooplankton samples were collected during the 1974 field season in the western and central basins of Lake Erie as part of the EPA Nutrient Control Project funded by the U.S. Environmental Protection Agency and administered by The Ohio State University, Center for Lake Erie Area Research. This phase of the nutrient study was designed to provide a comprehensive collection of information on the species and numbers of the major zooplankton groups in the western and central basins, in addition to relating biomass of these animals to other physical, chemical and biological parameters.

METHODS

During six cruises between May and November of 1974, 51 stations throughout the western and central basins were visited (see Overview, Section 1, Figure 1). Zooplankton samples were collected by vertical tow using a 0.5 meter, 80-micron mesh net which was raised mechanically at a constant rate. Organisms were relaxed with club soda and then preserved in five percent $MgCO_3$ buffered formalin.

At the Columbus laboratory, samples were counted using a stratified method allowing for enumeration of approximately 200 adult crustaceans and 250-300 immature crustaceans and rotifers. With a Wild M5 binocular dissecting microscope at 50x in conjunction with a Ward zooplankton counting wheel, copepods, cladocerans and rotifers were identified to species, excepting immature forms. The open chamber permitted manipulation and dissection of individuals when necessary for identification.

Distinction was made between male and female adult crustaceans, and all gravid or egg-carrying female animals were enumerated separately and numbers of young or eggs noted. Nauplii of the cyclopoid and calanoid species were counted together, but the nauplii were grouped into three size classes. The cyclopoid and calanoid copepodids were each separated into three size classes. Adult cladocerans were also placed into three size classes. The rotifers were identified to species whenever possible. All rotifers carrying eggs are listed separately, and number of eggs per individual recorded.

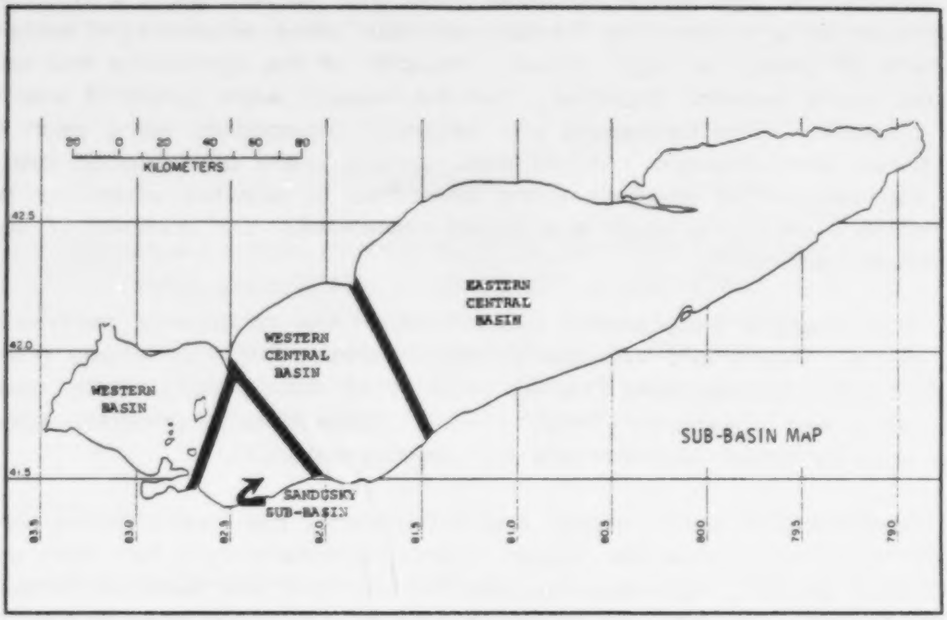
For routine zooplankton identification the taxonomic references used were: Ward and Whipple (1959), Pennak (1953), Jahoda (1948), Voigt (1957), Deevey and Deevey (1971), Brooks (1957), Eddy and Hodson (1961) and Ahlstrom (1940, 1943). Occasionally problem species were sent to other taxonomists for confirmation.

Numbers per cubic meter and milligrams per cubic meter of dry weight were calculated and basin averages determined for each species and major group. Biomass values for the rotifers were obtained by assigning each species a geometric configuration approximating its shape, determining a volume and assuming a specific gravity of one. Dry weight was calculated by taking 10 percent of the wet weight as recommended by Ruttner-Kolisko (1974). Biomass estimates for the cladocerans and copepods were obtained from Dumont, et al. (1975), Makarewicz (1974), Nauwerck (1963), Wilson and Roff (1973) and through personal communication of unpublished data by J.B. Wilson of the Canada Centre for Inland Waters.

Based on depth and chemical parameters the western and central basins were further divided into the western basin, Sandusky sub-basin, western central basin and eastern central basin (Figure 104). These subbasins proved valuable in evaluation of distribution of major zooplankton groups and individual species as the seasons progressed.

NET EFFICIENCY

Differences in net mesh size may result in disproportionate numbers of zooplankters being captured. If the mesh is large many small organisms are lost, but small mesh nets may cause serious clogging problems resulting in an inaccurate representation of numbers or organisms per cubic meter of water. Many zooplankton surveys have assumed a net efficiency of 100 percent, and therefore numbers of organisms presented are probably lower than actually occur in the water column. According to McNaught, et al. (1975), estimates of zooplankton biomass based on 100 percent net efficiency are usually low by a factor of two and often by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KILOMETERS
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82.5
82.0
81.5
81.0
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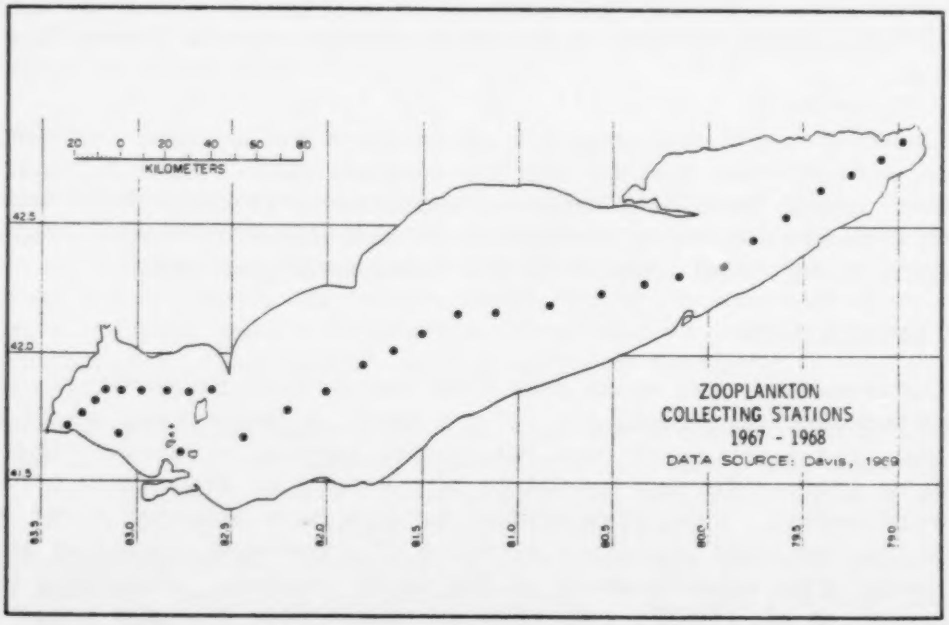
80.0
79.5
79.0
WESTERN BASIN
WESTERN CENTRAL BASIN
EASTERN CENTRAL BASIN
SANDUSKY SUB-BASIN
SUB-BASIN MAP

Figure 104. Sub-basin map.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KILOMETERS
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80.0
79.5
79.0
ZOOPLANKTON
COLLECTING STATIONS
1967 - 1968
DATA SOURCE: Davis, 1969

Figure 105. Zooplankton collecting stations 1967-1968.

as much as a factor of ten. The average net efficiency during this study, as determined by two flow meters mounted on the inside and outside of the net, was approximately 70 percent based on spring, summer and fall measurements. Numbers per cubic meter were adjusted based on this percentage.

PREVIOUS STUDIES

During the past ten years there have been three extensive Lake Erie zooplankton surveys. Davis (1969) made two transects of the entire lake in July and October of 1967 and a partial transect in January of 1968. He visited 30 stations located mid-lake (Figure 105) and identified and counted copepods, cladocerans and rotifers. Watson and Carpenter (1974) sampled crustacean zooplankton at 30 stations throughout the western, central and eastern basins from April to December of 1970 (Figure 106). Patalas (1972) traversed the entire lake to sample crustacean zooplankton at 34 stations during two cruises between June and August of 1972 (Figure 107).

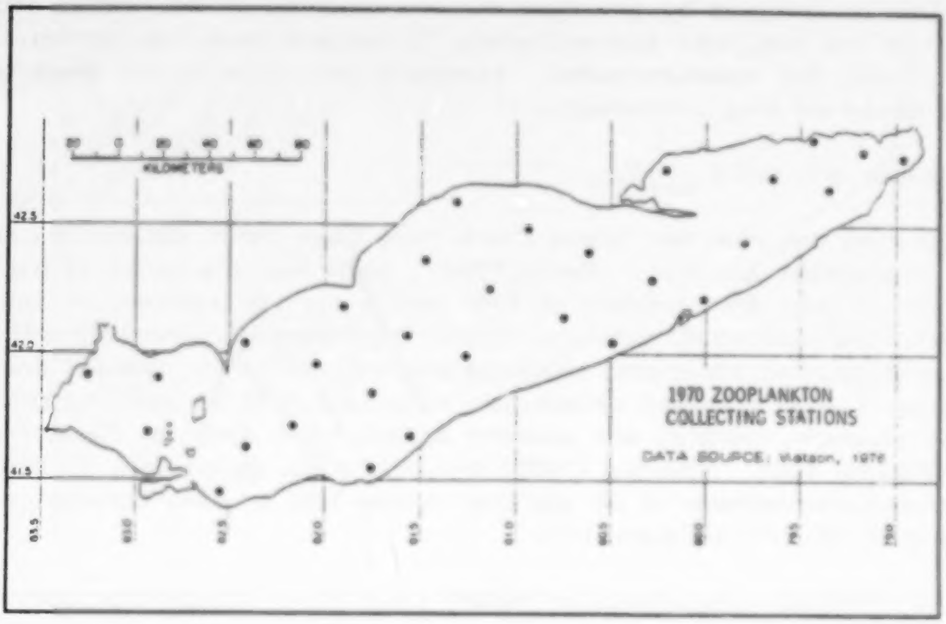
A methods comparison of recent Lake Erie zooplankton surveys is presented as Table 68. Differences in sampling techniques, length of field season, cruise frequency, net size, counting techniques and the plankton groups examined are apparent when the surveys are contrasted. These differences in technique make comparison of surveys difficult.

RESULTS

Total Zooplankters

Peak concentrations of total zooplankters were observed during early June and early September in the western central and eastern central sub-basins, but this bimodal pattern did not occur in the western basin and Sandusky sub-basin (Figure 108, Table 69). Zooplankton numbers per cubic meter increased rapidly in the western and central basins after a spring low, and remained stable during June and July. Populations in the two western sub-basins maintained this high level from mid-August through the end of October, while levels in the central basin dropped sharply in mid-August. This low was followed by an increase in early September and a decline at the end of October.

Discussion of the three major zooplankton groups will be presented in the following sections. A list of species identified from the western and central basins during 1974 appears as Table 70.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42.0
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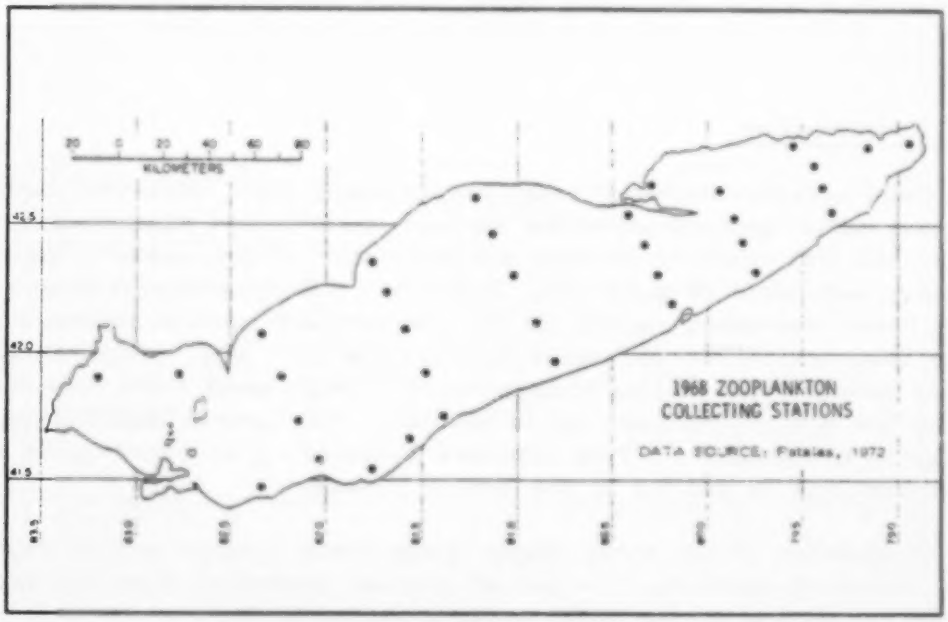
1970 ZOOPLANKTON COLLECTING STATIONS
DATA SOURCE: Watson, 1976

Figure 106. 1970 zooplankton collecting stations.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KILOMETERS
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1968 ZOOPLANKTON COLLECTING STATIONS
DATA SOURCE: Patalas, 1972

Figure 107. 1968 zooplankton collecting stations.

TABLE 68. LAKE ERIE ZOOPLANKTON STUDIES COMPARATIVE METHODS

Investigator(s)	Year	Season	Basin, # Stations # Cruises	Collecting Method, Net Size	Groups Considered	Counting Method
Engel (1962)	1961	June–August	Western Basin 6 cruises 6 stations	Juday Trap 64μ net	rotifers, crustaceans	Sedgewick Rafter cell
Davis (1969)	1967–1968	July, October, 1967, January, 1968	All Basins 30 stations 3 cruises	VT, 0.5m, 64μ	rotifers, crustaceans	Sedgewick Rafter cell
Watson and Carpenter (1974)	1970	April – December	All basins 30 stations 10 cruises	VT, 0.4m, 64μ	crustaceans	Inverted microscope
Patalas (1972)	1972	June – August	All basins 34 stations 2 cruises	VT, 0.12m, 90μ	crustaceans	----
Rolan, Zack and Pritschau (1973)	1973	September, 1971 to January, 1973	Cleveland Harbor 10 stations monthly	VT, 0.5m, 76μ	crustaceans	open counting chamber
CLEAR (unpublished)	1974	May – November	CB, WB 50 stations 6 cruises	VT, 0.5m, 80μ	rotifers, crustaceans	open counting chamber
Great Lakes Laboratory (unpublished)	1974	March–November	Eastern Basin 25 stations 6 cruises	VT, 0.5m, 64μ	crustaceans	open counting chamber

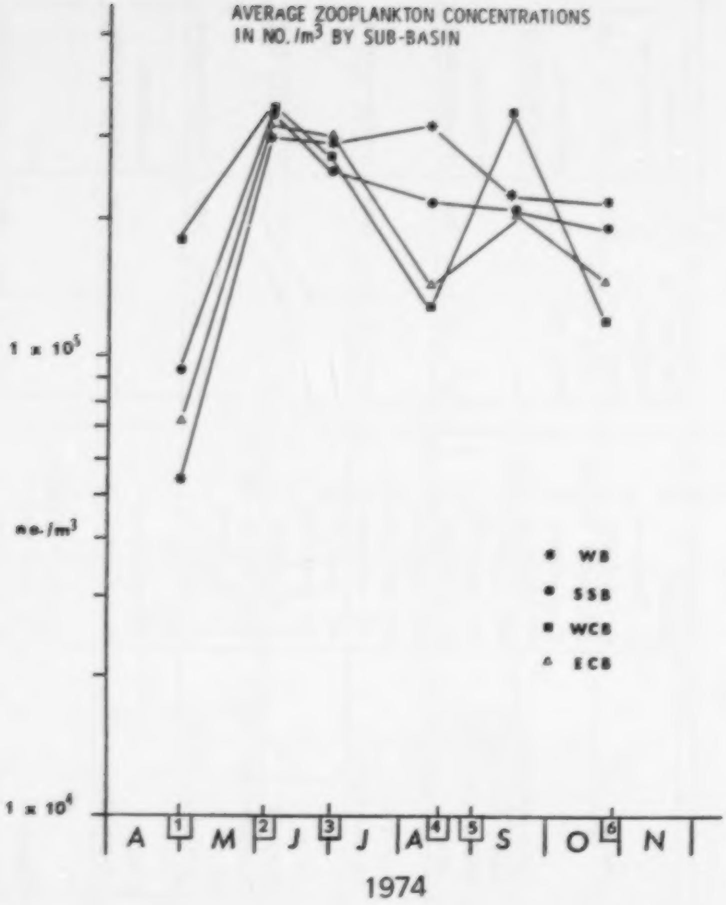

Figure 108. Average zooplankton concentrations in no./m^3 by sub-basin.

TABLE 69. AVERAGE 1974 ZOOPLANKTON NUMBERS/m^3 BY BASIN AND CRUISE

	Group	Western	"B"	WCB	ECB	Shore
1	Rotifers	1.5×10^{4}	3.6×10^{4}	9.3×10^{4}	3.6×10^{4}	5.7×10^{4}
	Cladocerans	3.0×10^{2}	1.1×10^{3}	2.5×10^{3}	7.6×10^{2}	1.7×10^{3}
	Copepods	3.9×10^{4}	5.7×10^{4}	8.6×10^{4}	3.5×10^{4}	7.9×10^{4}
	Total	5.43×10^{4}	9.41×10^{4}	1.815×10^{5}	7.176×10^{4}	1.377×10^{5}
2	Rotifers	2.1×10^{5}	1.0×10^{5}	3.8×10^{4}	6.6×10^{4}	7.2×10^{4}
	Cladocerans	4.8×10^{4}	1.0×10^{5}	6.4×10^{4}	5.3×10^{4}	8.9×10^{4}
	Copepods	8.6×10^{4}	1.2×105	2.0×10^{5}	2.0×10^{5}	2.0×10^{5}
	Total	3.44×10^{5}	3.4×10^{5}	3.02×10^{5}	3.19×10^{5}	3.61×10^{5}
3	Rotifers	1.2×10^{5}	4.1×10^{4}	3.5×10^{4}	4.2×10^{4}	4.6×10^{4}
	Cladocerans	5.5×10^{4}	4.3×10^{4}	5.1×10^{4}	8.2×10^{4}	7.8×10^{4}
	Copepods	1.2×10^{5}	1.7×10^{5}	1.9×10^{5}	1.8×10^{5}	1.9×105
	Total	2.95×10^{5}	2.53×10^{5}	2.76×10^{5}	3.04×10^{5}	3.14×10^{5}
4	Rotifers	2.5×10^{5}	1.8×10^{5}	6.7×10^{4}	4.9×10^{4}	7.7×10^{4}
	Cladocerans	1.4×10^{4}	1.1×10^{4}	1.7×10^{4}	1.9×10^{4}	2.3×10^{4}
	Copepods	5.8×10^{4}	2.7×10^{4}	4.5×10^{4}	7.6×10^{4}	6.5×10^{4}
	Total	3.22×10^{5}	2.18×10^{5}	1.29×10^{5}	1.44×10^{5}	1.65×10^{5}
5	Rotifers	1.6×10^{5}	1.1×105	2.4×10^{5}	1.3×10^{5}	2.4×10^{5}
	Cladocerans	3.8×10^{4}	5.6×10^{4}	6.7×10^{4}	2.8×10^{4}	5.9×10^{4}
	Copepods	3.2×10^{4}	4.5×10^{4}	4.1×10^{4}	4.6×10^{4}	4.4×10^{4}
	Total	2.3×10^{5}	2.11×10^{5}	3.48×10^{5}	2.04×10^{5}	3.43×10^{5}
6	Rotifers	1.9×10^{5}	1.1×10^{5}	3.6×10^{4}	4.0×10^{4}	6.0×10^{4}
	Cladocerans	1.5×10^{4}	4.5×10^{4}	3.7×10^{4}	5.0×10^{4}	5.5×10^{4}
	Copepods	1.6×10^{4}	3.6×10^{4}	4.7×10^{4}	5.7×10^{4}	5.5×10^{4}
	Total	2.21×10^{5}	1.91×10^{5}	1.2×10^{5}	1.47×10^{5}	1.7×10^{5}

TABLE 70. ZOOPLANKTON SPECIES FOUND IN WESTERN AND CENTRAL BASINS OF LAKE ERIE, 1974 AND 1975

Rotifers

Asplanchna priodonta
Brachionus angularis
B. budapestiensis
B. calyciflorus
B. caudatus
B. havanaensis
B. diversicornus
B. patulus
B. quadridentatus
B. urceolaris
Chromogaster ovalis
Cephalodella sp.
Collotheca pellagica
Conochiloides dossuarius
Conochilis unicornus
Euchlanis dilitata
Filinia longiseta
Kellicottia longispina
Keratella cochlearis
K. cochlearis fo. tecta
Keratella crassa
K. quadrata
K. hiemalis
Lecane luna
Rotaria sp.
Hexarthra mira
Notholca foliacea
N. acuminata
N. laurentia
N. squamula
Pleosoma lenticulare
P. hudsonii
P. truncatum
Pomphlyx sulcata
Polyarthra vulgaris
P. dolichoptera
P. euryptera
P. longiremis
P. major
P. remata
Synchaeta lakowitziana
S. oblonga
S. pectinata
Synchaeta sp.
Trichocerca cylindrica
T. multicrinis
T. similis
T. longiseta

Cladocerans

Alona affinis
Bosmina longirostris
Ceriodaphnia lacustris
Chydorus sphaericus
Daphnia ambiqua
D. galeata
D. longiremis
D. parvula
D. retrocurva
Polyphemus pediculus
Sida crystallina
Diaphanosoma leuchtenbergianum
Eubosmina coregoni
Eurycercus lamellatus
Holopedium gibberum
Ilyocryptus sordidus
Latonia setifera
Ledigia quadrangularis
Leptodora kindtii
Moina brachiata
Pleuroxus procurvas

Copepods

Cyclops bicuspidatus thomasi
C. vernalis
Mesocyclops edax
Eucyclops agilis
E. speratus
Tropocyclops prasinus
Paracyclops fimbriatus poppei
Diaptomus ashlandii
D. oregonensis
D. sicilis
D. siciloides
D. minutus
Eurytemora affinis
Epischura lacustris
Limnocalanus macrurus
Canthocamptus robertcokeri

Rotifers

Due to their relatively low biomass and taxonomic problems, many plankton investigators have chosen to exclude the rotifers from zooplankton population studies. Small in size compared to the copepods and cladocerans, rotifers were found by Schindler and Novén (1971) to comprise no more than 12 percent of the zooplankton biomass in several lakes characterized as oligotrophic to eutrophic. In contrast, during 1974 rotifers in the enriched western basin of Lake Erie comprised 6 to 40 percent of the total zooplankton biomass. Based on studies in Lakes Michigan and Huron, Gannon and Stemberger (1975) concluded that such high populations of rotifers may be considered indicative of eutrophic waters. Because their rapid reproductive rates make them quick to respond to environmental changes, rotifers may be valuable as indicator organisms.

Only two investigators since 1960 have included rotifers in Lake Erie surveys. Secoy (1962) identified 201 species of rotifers from the island region of Lake Erie in 1960. When comparing her study to those of Ahlstrom (1934), Chandler (1940), Kellicott (1896, 1897) and Jennings (1901) she found that 106 of the 201 species had been found by more than one of the previous workers, and only six species were common to all surveys. Davis (1969) sampled in July, October and January and found highest rotifer concentrations and number of species in the western basin during July and October.

The species list which appears as Table 70 includes 47 rotifer taxa identified from 1974 collections. Most of the species are planktonic and ubiquitous in distribution. The littoral-benthic organisms which are listed were found only occasionally as accidental members of the plankton community.

Lake Erie Western and Central Basin Rotifers

During the 1974 May to November field season, rotifer populations demonstrated bimodal increases with a mid-summer decline (Figure 109). Numbers were low in early May in all but the western central basin, where large populations of *Notholca* spp. were found, primarily *N. laurentiae*.

By early June, rotifer numbers were high in the western and Sandusky sub-basins and the community was dominated by *Keratella quadrata*, *K. cochlearis*, *Conochilus unicornus* and *Polyarthra vulgaris*. Fewer rotifers were collected in the central basin during early June. Dominant members of the central basin community were *K. quadrata*, *Polyarthra dolichoptera* and *P. vulgaris*.

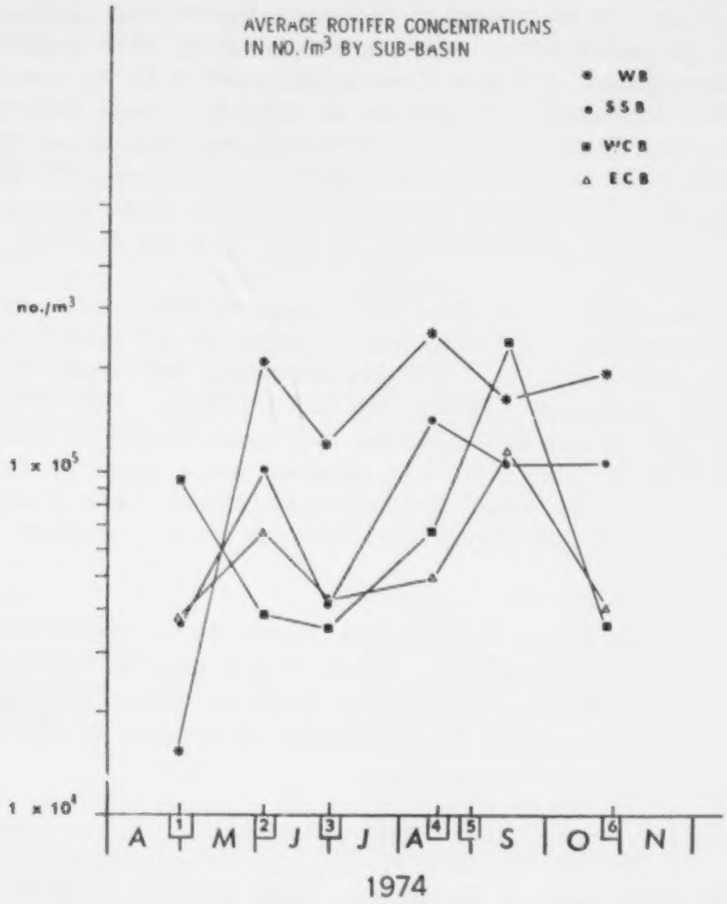

Figure 109. Average rotifer concentrations in no./m^3 by sub-basin.

The first half of July brought a drop in rotifer populations, although levels remained comparatively high in the western basin. The high western basin concentrations were mainly due to peak populations of C. unicornus and Brachionus budapestiensis.

The second pulse in the rotifer community occurred during mid-August in the western basin and Sandusky sub-basin, and early September in the western central and eastern central sub-basins. The mid-August pulse was the result of large numbers of Brachionus angularis in the western basin and a peak concentration of Asplanchna priodonta in the Sandusky sub-basin. The high levels in early September in the western central and eastern central basins resulted from large numbers of C. unicornus, K. cochlearis, Trichocerca spp. and Polyarthra major.

By late October of 1974 rotifer populations had declined in the central sub-basins but remained high in the western basin and Sandusky sub-basin. The western basin community was dominated by Synchaeta spp. and Brachionus calyciflorus and the Sandusky sub-basin primarily by Synchaeta spp.

Rotifers were abundant in both basins during 1974. The western basin is the shallowest and most nutrient-rich area, and had the highest numbers of rotifers during most of the 1974 sampling season.

Due to high turnover rates and rapid restructuring of the rotifer community resulting from environmental changes, sampling during 1974 may not have been frequent enough to reflect seasonal successional patterns within this group.

Cladocerans

Patalas (1972), as well as other zooplankton ecologists, consider large numbers of cladocerans to be indicative of eutrophic conditions. In 1961 Engel (1962) noted an increase in cladoceran populations in western Lake Erie since Chandler's 1938-39 survey, and especially a rise in the numbers of Chydorus sphaericus, which is considered an indicator of eutrophic conditions. An increase in Lake Erie cladoceran populations since 1939 was also noted by Bradshaw (1964), who compared his 1949 data to those of Chandler (1940) and Hubschman (1960).

Watson and Carpenter (1974) found cladocerans more numerous in Lake Erie than in Lakes Ontario and Huron, with populations especially high in the western and central basins of Lake Erie. Patalas (1972) compared Lakes Superior, Huron and Erie and noted that as eutrophication progressed, percentages of calanoid copepods declined and percentages of cladocerans and cyclopoid copepods increased. Numbers of cladocerans were found to be highest in the western basin of Lake Erie during Patalas' survey.

Lake Erie Western and Central Basin Cladocerans

From May to November of 1974, cladoceran concentrations in the four sub-basins were very similar and bimodal peaks were concurrent in all basins (Figure 110). In early May cladocerans occurred at low concentrations. By the early June cruise high numbers had been reached, remained stable through the July cruise, and declined sharply by mid-August in all sub-basins. Early September brought a second pulse, nearly equalling that which occurred in the early summer. Populations remained high in all but the western basin until November.

The major component of the early summer cladoceran pulse was *Bosmina longirostris*. This cladoceran reached its highest concentration in the Sandusky sub-basin and was found in lowest numbers in the western basin. *Eubosmina coregoni* was the most numerous cladoceran in the western basin, but occurred in low concentrations elsewhere. *Daphnia retrocurva* was also abundant during the first half of the summer, and occurred in highest concentrations in the western and Sandusky sub-basins.

The early September pulse was dominated by *Bosmina longirostris*, *Eubosmina coregoni* and *Daphnia galeata mendotae*. *Eubosmina coregoni* was found in greatest numbers in the western and Sandusky sub-basins, *Bosmina longirostris* reached highest concentrations in the western central basin, and *D. galeata mendotae* was restricted to the western central and eastern central basins.

By the end of October *E. coregoni*, *B. longirostris* and *Chydorus sphaericus* dominated the cladoceran community. The seasonal peak of *C. sphaericus* was observed during the late October cruise. This species was found in high concentrations in all but the western basin, where it was declining after a mid-August maximum. *Eubosmina coregoni* populations were highest in the eastern central basin and lowest in the western basin in October. *Bosmina longirostris* was found in highest numbers in the Sandusky sub-basin and western basin, with lower concentrations observed in the central basin.

Cladocerans comprised less than 10 percent of the total zooplankton biomass (mg/m^3) during early May. By early September they made up over 55 percent of the zooplankton biomass in all of the sub-basins and were of greatest importance in the western and Sandusky sub-basins where enriched conditions seem to be most favorable for their reproduction and growth.

Copepods

Patalas (1972) considered the differences in the crustacean populations of Lakes Superior, Erie, Huron and Ontario to be due to differences in

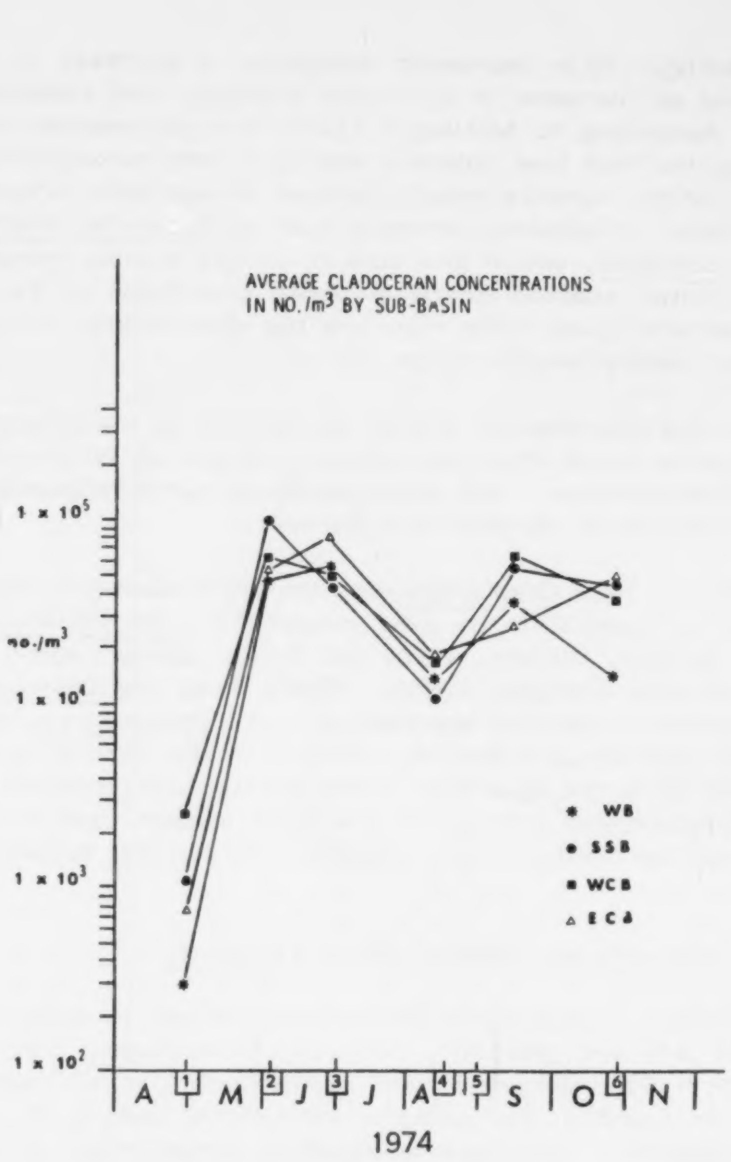

Figure 110. Average cladoceran concentrations in no./m^3 by sub-basin.

nutrient loading. With increased nutrients, a decrease in calanoid copepods and an increase in cyclopoid copepods and cladocerans was apparent. According to McNaught (1975) this succession may be better explained by the fact that calanoid copepods are nannoplankton feeders, while many of the species most abundant in eutrophic waters are generalist feeders. Therefore animals such as *Bosmina longirostris* and *Eubosmina coregoni*, which are able to utilize a wide range of particle sizes, are better adapted to the enriched conditions of the central and western basins of Lake Erie than are the diaptomids, which utilize particles in the nannoplankton range.

Gannon and Stemberger (1975) stated that in the oligotrophic offshore waters of Lake Michigan calanoids made up 50 percent of the total microcrustaceans. But onshore where nutrient concentrations were high, calanoids made up only five percent.

In 1928 and 1929 *Diaptomus* was the most abundant copepod in the eastern half of Lake Erie in July (except for *Limnocalanus* located in the deeper waters, Wilson, 1960) and in the island region of the western basin in 1930 (Wright, 1955). Since then, the *Diaptomus* copepods have decreased in relative abundance, and *Limnocalanus* has nearly disappeared (Gannon and Beeton, 1971). In the central and western basins of Lake Erie the calanoids were greatly outnumbered by the cyclopoids and cladocerans throughout the 1974 season, and this trend was also observed by Davis (1969), Patalas (1972), and Watson and Carpenter (1974).

Lake Erie Western and Central Basin Copepods

The average copepod populations were small in early May, peaking in June and July and gradually declining from August through October (Figure 111). This general trend was apparent in all four sub-basins. The copepods found in the western and central basins of Lake Erie were mainly cyclopoids. Although calanoids at times made up about 30 percent of the copepod biomass, they were never as numerous as the cyclopoids. One harpactocoid copepod, *Canthocamptus robertcokeri*, was found only in low numbers early in the season in the western portion of the lake.

Of the cyclopoid copepods, *Cyclops bicuspidatus thomasi* was most numerous during June and July, especially in the western basin and Sandusky sub-basin. This copepod nearly disappeared from the western and Sandusky sub-basins by August, but remained common in the central basin through October. The *Cyclops vernalis* population reached a peak in early July in the western basin and outnumbered *C. bicuspidatus thomasi*. *Cyclops vernalis* was also abundant in the Sandusky sub-basin,

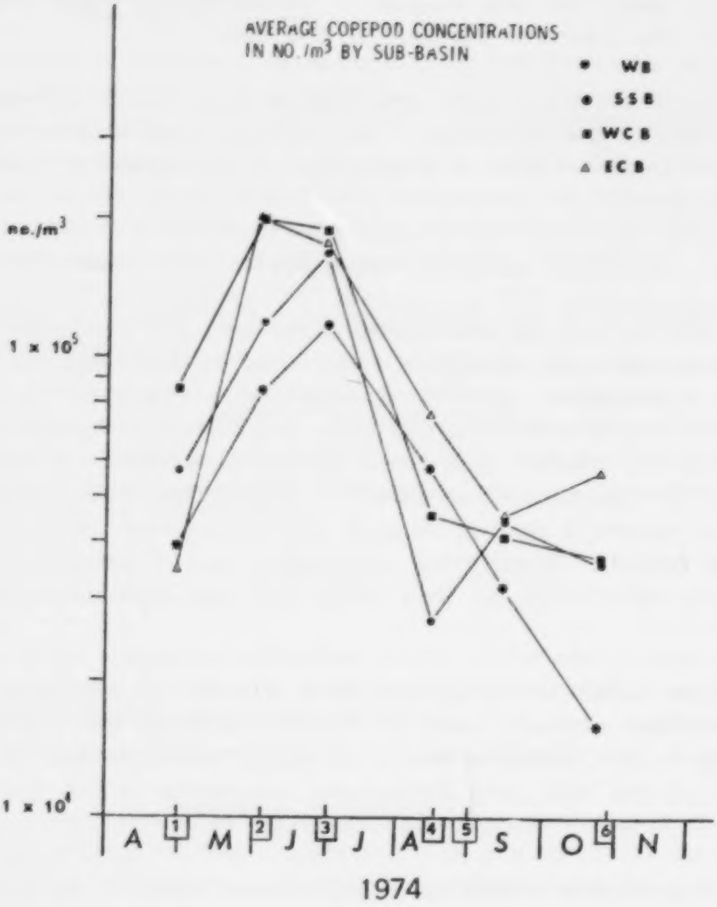

Figure 111. Average copepod concentrations in no./m^3 by sub-basin.

although it was greatly outnumbered by *C. bicuspidatus thomasi*, and was nearly excluded from the central basin throughout the sampling period.

Mesocyclops edax was abundant in the central basin during the second half of the summer, with maximum populations observed in the eastern central basin in late August. *Mesocyclops edax* was seldom collected from the western portion of the lake.

Tropocyclops prasinus var. *mexicanus* was found in relatively low numbers throughout the summer. Its highest populations occurred in September and October with a maximum in the eastern central basin during late October.

The most important calanoid copepods in 1974 were the diaptomids: *Diaptomus oregonensis*, *D. siciloides*, *D. ashlandii*, *D. minutis*, and *D. sicilis*. During spring and early summer, *D. ashlandii* and *D. siciloides* were the most abundant calanoids in the western basin and the Sandusky sub-basin. *Diaptomus ashlandii* was also found in the western central basin and was the only diaptomid common in the central basin at this time. After July, few diaptomids were collected in the western basin or Sandusky sub-basin. *Diaptomus oregonensis* was the most abundant calanoid during August and September and was restricted to the central basin. *Diaptomus siciloides* was a secondary compenent of the calanoid community at this time and was also confined to the central basin.

Three other calanoid copepods were found: *Limnocalanus macrurus* in the western and western central basins early in the summer; *Eurytemora affinis* in the western basin in early summer and in the eastern central basin in the fall; and *Epischura lacustris* in the Sandusky sub-basin in early June. These copepods were never found in abundance.

Immature copepods made up a significant portion of the zooplankton community. High numbers of nauplii were found in June in the central basin and July in the western and Sandusky sub-basin. During June and July the cyclopoid copepodid population was high, with the greatest concentrations found in the central basin. Calanoid copepodids occurred in relatively low concentrations in both basins throughout the summer.

Copepodid numbers were usually higher than nauplii numbers. This would indicate that many nauplii were lost through the 80-micron mesh of the net. When comparing levels of copepodids to adult copepods, it was evident that a large number of these immature forms did not develop into adults, probably due to predation.

FUTURE OBJECTIVES

Further analyses and comparisons of 1974 and 1975 data are yet to be completed. Biomass values for the most frequently encountered microcrustacean species will be obtained directly in the laboratory. Dry weight (mg/m^3) may therefore be calculated more accurately than by use of literature values alone.

In 1966, Williams stated that numbers of rotifers correlate directly to phytoplankton abundance. Glooschenko, et al. (1974) did not consider zooplankton numbers to be in phase with chlorophyll a or pheopigments, but claimed that the zooplankton food chain in Lake Erie is chiefly detrital and that living algae are more important as food in oligotrophic lakes. Patalas (1972) related crustacean abundance with degree of trophy, especially particulate phosphorus loading rates.

Attempts will be made to investigate some of these reports by correlating zooplankton biomass and community structure with parameters such as temperature, chlorophyll, particulate carbon, particulate phosphorus, particulate nitrogen and turbidity. Statistical analyses will hopefully provide insight into community structure within the basins and throughout the season and also determine variability due to sampling and counting methods.

SUMMARY

1. Zooplankton samples collected from 51 western and central basin stations during the May to November field season of 1974 were analyzed to determine species composition and seasonal succession of rotifers, cladocerans and copepods.

2. In spite of their small size, rotifers comprised a significant percentage of the zooplankton biomass (6-40 percent in the western basin). Numerical differences in rotifer concentrations from basin to basin were quite dramatic.

3. During 1974, high numbers of cladocerans were observed in both basins, with early summer and autumn pulses. Cladocerans comprised the highest percentage of the zooplankton biomass during the late summer and fall.

4. Cyclopoid copepods were dominant over calanoid copepods throughout the 1974 field season. The greatest numbers of copepods occurred during June and July in both basins, and numbers declined steadily through the remainder of the sampling season.

5. High numbers of rotifers occurred during 1974 in the western and central basins of Lake Erie, and such high concentrations are considered indicative of enriched conditions. Cladoceran numbers have increased steadily since 1939, and this group currently has higher concentrations in the western basin of Lake Erie than elsewhere in the Great Lakes. Through the years, cladocerans and cyclopoid copepods have gradually outnumbered the once dominant calanoid copepods. The trend from a calanoid-dominated to a cyclopoid and cladoceran-dominated community has been observed during studies of other lakes which have undergone nutrient enrichment.

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SECTION 10

BENTHIC MACROINVERTEBRATE DISTRIBUTIONS IN THE CENTRAL AND WESTERN BASINS OF LAKE ERIE

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INTRODUCTION

Lake Erie has been a discussion topic for a number of years due to its status as a polluted body of water. Changes in the lake's water quality and its biota have been noted throughout the last century (Beeton, 1961; Brinkhurst et al., 1968; Britt, 1955; Britt et al., 1973; Brown, 1953; Burns and Ross, 1972; Carr and Hiltunen, 1965; Federal Water Pollution Control Administration, 1968; Herdendorf et al., 1974; Hiltunen, 1969; Langlois, 1954; Shelford and Boesel, 1942; Osburn, 1926; Wood, 1953 and 1963; Wright, 1955). In most cases, the conclusions of their studies indicated degradation of Lake Erie's waters.

Aspects of water quality degradation involve: 1) increased sediment loadings, 2) increased turbidities, 3) higher bacterial counts (particularly of the coliform bacteria), 4) increase in the number and frequency of nuisance algal blooms, 5) an increasingly larger area of the bottom becoming anoxic, 6) decreasing fish populations, 7) shifts in the bottom fauna from sensitive forms to tolerant forms, and 8) increased loading and regeneration of major algal nutrients (particularly phosphorus and nitrogen). To alleviate degradation, both the United States and Canada began to implement control measures designed to reduce the level of waste and nutrient inputs into Lake Erie. To evaluate the efficacy of these measures upon Lake Erie waters, a multidisciplinary approach project was initiated by the Center for Lake Erie Area Research (1974). This assessment consists of monitoring several physical, chemical and biological components of the Lake Erie ecosystem. This particular subproject was designed to examine Lake Erie's benthic macroinvertebrate communities.

METHODS

Duplicate Ponar grab samples (0.555 m^2) were taken at each of 52 stations in Lake Erie's western and central basins during cruises aboard Ohio State University's research vessel, R/V Hydra. During the initial stages of the project several research vessels were used including: R/V Dambach (Great Lakes Laboratory, SUNY), R/V Maple (Great Lakes Research Division, University of Michigan), and P/B Bluewater (Gross Ile Laboratory, USEPA).

Samples were taken during ice-free months June 1973 through December 1975 for a total of 15 benthological cruises (Table 71). The results of nine cruises, June 1973 through October 1974, are discussed here.

TABLE 71. SAMPLING PERIODS FOR LAKE ERIE NUTRIENT STUDY - BENTHOS CRUISES

Cruise Number		Date
1	1973	28 June - 12 July
2		17 July - 23 July
5		29 August - 4 September
7		14 October - 24 October
2	1974	25 April - 4 May
4		1 June - 10 June
6		26 July - 4 August
8		26 August - 7 September
10		21 October - 1 November

The Ponar samples were taken with a power winch and wet seived on board through a U.S. Soil Series No. 49 screen. The retained material was washed into plastic jars and preserved. The samples initially were preserved with 10 percent formalin, but the 1975 samples were preserved with AGW (alcohol:glycerine:water in a 70:5:25 mixture). The samples were then labeled and stored until analyzed.

The stored samples were stained with Rose Bengal solution and sorted into Oligochaeta and non-Oligochaeta fractions. Non-oligochaetes were identified by Dr. N.W. Britt. The oligochaetes were initially identified by Dr. E.M. Hair and later by A.J. Pliodzinskas. Enumeration and identification proceeded simultaneously.

ORGANISM DISTRIBUTION, DENSITY AND DIVERSITY

Organism distributions and their abundances are the results of various interactions of the biotic and abiotic components of the environment. In the open waters of Lake Erie's western and central basins during the 1973 and 1974 sampling seasons, the benthic macroinvertebrate fauna is composed of at least 66 taxa, identified to species where possible. Thirty-six of these taxa are found throughout both basins, while eleven and nineteen are limited to the western and central basins, respectively (Tables 72 and 73).

The number of different taxa per square meter or diversity found throughout the lake varies among stations and with time (Table 74). Average diversity of samples (1973-1974) indicates that the lake bottom can be divided into four general zones of diversity (Figure 112). The boundaries of these zones presented herein should not be considered absolute as they are interpretations of the combined data.

Zone I, areas of lowest diversity, is to be found: 1) along the northeastern edge of the central basin (stations 28 and 29), 2) south of Pelee Point (station 50), and 3) just west of Fairport Harbor (station 35). The Zone I stations were the least successfully sampled stations during the 1973 and 1974 seasons due primarily to substrate type and secondarily to adverse weather conditions. These stations have either sand or sand/gravel veneered clay substrates which reduce the effectiveness of the Ponar sampler (Figure 113). Generally, these types of substrates are inhospitable to sedentary organisms due to the grinding action of the sediments during current activity (Purdy, 1967, Figure 114). In addition, sandy regions are relatively turbulent and result in little detritus settling out and remaining in the sediments; subsequently, there is little food resource available. It is much more difficult for small organisms to burrow in sand than in mud because of the difference in particle size and in the ability of the organism to make cohesive burrows in each sediment type.

Zone II (4-7 taxa) lies primarily within the 20-25-meter depth zone (Figure 115) and substrates consisting of soft, silty, grey mud with the major fraction consisting of clay. The Zone II region consists of four separate areas. The largest area encompasses much of the south side of the western half of the central basin up to about midway between Cleveland and Fairport Harbor. Two other areas of Zone II are located in the eastern half of the central basin, one in the middle-eastern section and one in the north-central section of the sub-basin. Along the western edge of the lake is the fourth Zone II region. This area lies in depths of six meters and has a substrate consisting of soft grey mud

TABLE 72. TAXANOMIC GROUPS FOUND IN LAKE ERIE'S WESTERN AND CENTRAL BASINS DURING LAKE ERIE NUTRIENT STUDY (1973-1974)

- ANNELIDA
  - Hirudinea
    - *Helobdella elongata*
    - *H. stagnalis*
    - *H. fusca*
    - *Glossiphonia complanata*
    - *G. heteroclita*
    - *Erpobdella punctata*
  - Polychaeta
    - *Manayunkia speciosa*
  - Oligochaeta
    - *Aulodrilus americanus*
    - *A. limnobius*
    - *A. pluriseta*
    - *Branchiura sowerbyi*
    - *Ilyodrilus templetoni*
    - *Limnodrilus cervix*
    - *L. cervix variant*
    - *L. claperedeianus*
    - *L. hoffmeisteri*
    - *L. maumeensis*
    - *L. spiralis*
    - *L. udekemianus*
    - *Peloscolex ferox*
    - *P. multisetosus*
    - *Potamothrix moldaviensis*
    - *P. vejdovskyi*
    - *Tubifex tubifex*
    - *Arcteonais lomondi*
    - *Dero digitata*
    - *Nais sp.*
    - *Ophidonais serpentina*
    - *Paranais foreli*
    - *P. longiseta*
    - *P. menoni*
    - *Stylaria lacustris*
    - *Vejdovskyella intermedia*
    - *Stylodrilus herringianus*
- ARTHROPODA
  - Crustacea
    - *Asellus r. racovitzai*
    - *Gammarus fasciatus*
    - *Pontoporeia affinis*
    - *Mysis relecta*
  - Insecta
    - *Oecetis sp.*
    - *Oecetis eddlistoni*
    - *Chironomus plumosus*
    - *C. riparius*
    - *C. (Cryptochironomus) sp.*
    - *Coelotanypus sp.*
    - *Metriocnemus sp.*
    - *Micropsectra sp.*
    - *Microtendipes sp.*
    - *Procladius sp.*
    - *Tanypus sp.*
    - *Tanytarsus sp.*
- MOLLUSCA
  - Gastropoda
    - *Physa sp.*
    - *Heliosoma sp.*
    - *Amnicola sp.*
    - *Bulimus tentaculata*
    - *Valvata sincera*
    - *V. tricarinata*
    - *Campeloma sp.*
    - *Goniobasis sp.*
    - *Somatogyra sp.*
  - Pelecypoda
    - *Ligumia recta*
    - *Lampsilis radiata luteola*
    - *Leptodea sp.*
    - *Pisidium sp.*
    - *Pisidium compressum*
    - *Sphaerium sp.*
- COELENTERATA
  - *Hydra sp.*
- PLATYHELMINTHES
  - *Planaridae*
  - *Rhabdocoela*

TABLE 73. BENTHIC FAUNA FOUND IN LAKE ERIE'S WESTERN AND CENTRAL BASINS

Western Basin	Central Basin	Both Basins	
Oecetis sp.	*Tanytarsus sp.*	*Helobdella stagnalis*	*Branchiura sowerbyi*
Oecetis eddlistoni	*Micropsectra sp.*	*H. elongata*	*Limnodrilus cervix*
Helobdella fusca	*Metriocnemus sp .*	*Erpobdella punctata*	*L. cervix variant*
Glossiphonia heteroclita	*Microtendipes sp .*	*Chironomus plumosus*	*L. claperdeianus*
G. complanata	*Pontoporeia affinis*	*C. riparius*	*L. hoffmeisteri*
Heliosoma sp .	*Aulodrilus americanus*	*C. (Cryptochironomus) sp.*	*L. maumeensis*
Campeloma sp .	*Ophidonais serpentina*	*Procladius sp.*	*L. spiralis*
Lampsilis r. luteola	*Arcteonais lomondi*	*Coelotanypus sp .*	*Peloscolex ferox*
Leptodea sp .	*Paranais foreli*	*Tanypus sp .*	*P. multisetosus*
Planaridae	*P. menoni*	*Gammarus faciatus*	*Potamothrix moldaviensis*
Limnodrilus udekemianus	*Nais sp .*	*Asellus r. racovitzai*	*P. vejdovskyi*
	Stylaria lacustris	*Amnicola sp.*	*Tubifex tubifex*
	Vejdovskyella intermedia	*Valvata sincera*	
	Paranais longiseta	*V. tricarinata*	
	Amphichaeta sp .	*Bulimus tentaculata*	
	Stylodrilus herringianus	*Somatogyra sp.*	
	Manayunkia speciosa	*Goniobasis sp.*	
	Mysis relicta	*Sphaerium sp.*	
	Hydra sp .	*Pisidium sp.*	
		P. compressum	
		Rhabdocoela	
		Physa sp.	
		Aulodrilus limnobius	
		A. pluriseta	

TABLE 74. BENTHIC MACROINVERTEBRATE DIVERSITY* IN LAKE ERIE'S WESTERN AND CENTRAL BASINS DURING LAKE ERIE NUTRIENT STUDY (1973-1974)

	Cruise Number									
Station Number	1	2	5	7	2	4	6	8	10	X
23	17	16	1	3			11			10
24	14	7	11			13	12		17	12
25	1	12		10					10	8
26	5	1	5							4
27	12	9	9	11					12	10
28	0	2	2							2
29	3	1								2
30	11	11	11	8	12	7	8	8	9	9
31	9	14	10	3	6	8	4	9	9	8
32	12		7	9	9	4	6	11	7	8
33	11	13		10	13	17	12	12		12
34	13	10		10	12	11	12	12	11	11
35	7	13	2							3
36	13	8	7	6	11	7	10	8	6	9
37	15	12	10	2	9	7	8	8	7	9
38		14	6	7		9	12	7	12	10
39	15	13	10	9		12	11	9		11
40	12		1				12			8
41	12	13	11	10	8	6	11		8	10
42	4		8	7	6	4	8	3	7	6
43	6	8	6	4	6	4	5	3	4	5
44	3	7	3					14		7
45		10	9	7	11	9		10	8	9
46	12	4		6	5	5	7	4	9	7
47	8	10	7		8	7	6	9	7	8
48		9		8				7		8
49	15	9	11	9			9	10	9	10
50	2	1								2
51	1	11	6	7			8	6	9	7
52	12	6	8	7	7	1	6	7	5	7
53	13	7	7	8	11	5		15		9
54	13	8	8	4	8	5	8	10	7	8
55				10						10
56	23	8	13	5	11	7	11	16	13	12
57	13	8	16	8	11	4		11	11	12
58	19	11	11	6	5	4	9	14	11	10
59	11	6		8	11	6	12	11	11	10
60	17	8		3	14	2	2	11	7	8
61	17	14	20	1		12	7	15	14	13
65					13	6	7	9		9
66	14	11	12	6	13		4	14	13	11
67	7	8	10	5	6	12	5	11	10	8
68	10	11	9	10	13	9	8	15	11	11
69	5				2					4
70	10	8	3	4	10	9	5		9	7
71	5	9	8	2						6
72			8	6						7
73	14	8	5		4	8	6	5	6	7
74		8	12	8	6	3	7	10	14	9
75	7	6	5	5		6	7	5		6
78					8	4	4	10	6	6
79						1		9		5
Mean	10	9	8	7	9	7	8	10	9	9
Stations Sampled	43	43	39	38	30	34	35	36	34	

* Diversity is expressed as number of different taxa present/m^2.

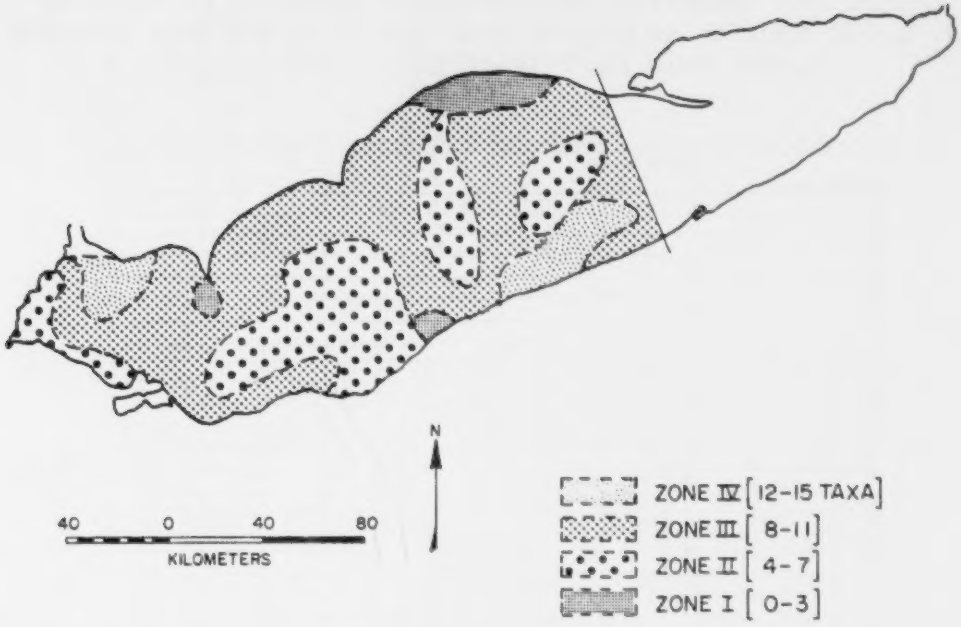

N
40
0
40
80
KILOMETERS
ZONE IV [12-15 TAXA]
ZONE III [8-11]
ZONE II [4-7]
ZONE I [0-3]

Figure 112. Average benthic macroinvertebrate diversity (Taxa number/m^2, 1973-1974).

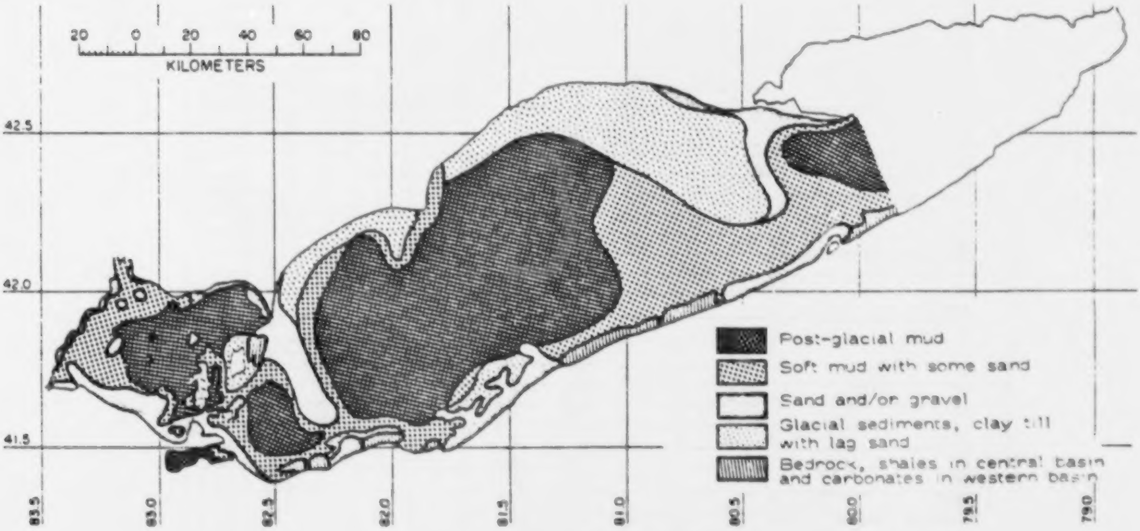
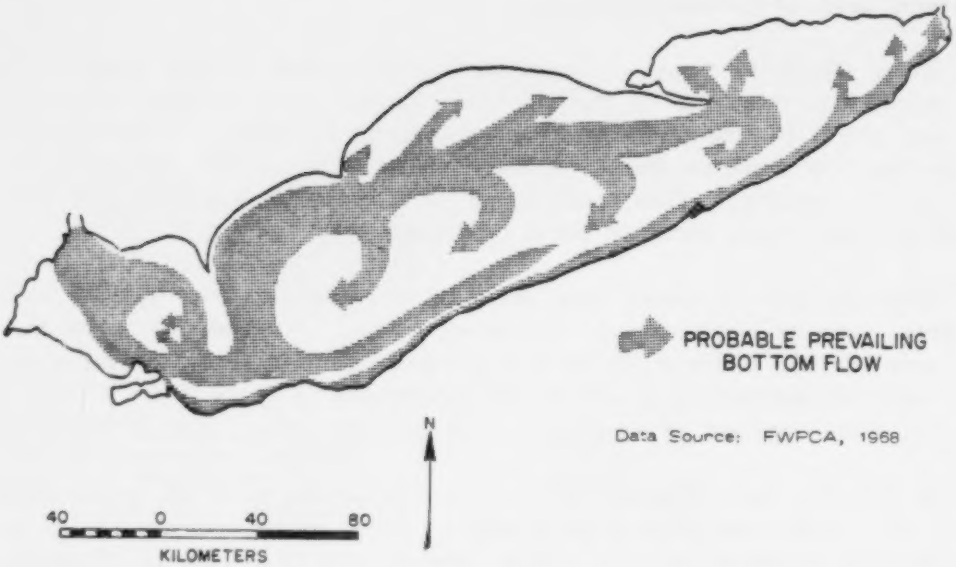

20
0
20
40
60
80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
Post-glacial mud
Soft mud with some sand
Sand and/or gravel
Glacial sediments, clay till with lag sand
Bedrock, shales in central basin and carbonates in western basin

Figure 113. Distribution of surficial sediments.


PROBABLE PREVAILING BOTTOM FLOW
N
40 0 40 80
KILOMETERS

Data Source: FWPCA, 1968

Figure 114. Prevailing annual bottom flow.

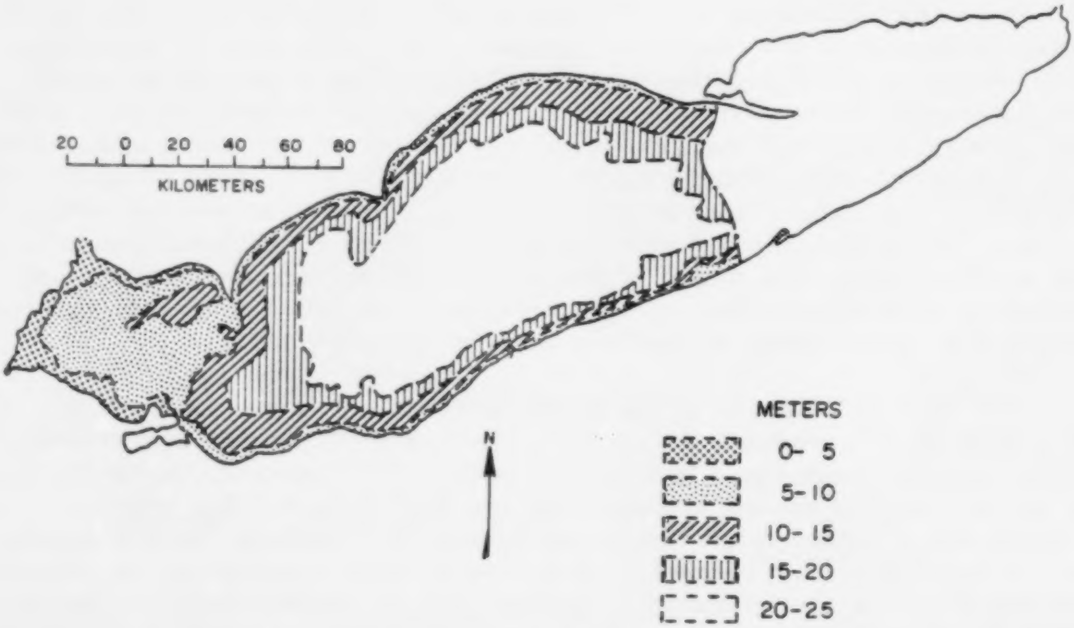

20 0 20 40 60 80
KILOMETERS
N
METERS
0- 5
5-10
10- 15
15-20
20-25

Figure 115. Lake Erie bathymetry.

with sand. These nearshore stations are at the mouth of the Maumee River, near the mouth of the Raisin River; at Locust Point; and in the western arm of Catawba Island.

Zone III (8-11 taxa) extends throughout most of the western basin and along the margins of the central basin. The largest section of Zone III lies along the northern part of the central basin. Depths in Zone III range from a shallow eight meters (station 60) to the deepest station (37) at 24 meters. The zone contains the greatest variety of substrates ranging from rock through sand to mud.

Zone IV (12-15 taxa), the zone of greatest diversity, has two components, one at each end of the study area. Farther west is the area just east of the Detroit River mouth and farther east is the area from just west of Ashtabula towards the northeast (Figure 112). The sediment type in both regions is identical, i.e., soft, grey, silty mud with sand.

A cursory examination of Figure 112 would give an incomplete assessment of macroinvertebrate diversity. Most of this diversity is the result of the presence of one major group, the Oligochaeta (Figure 116). The oligochaetes make up 40.9 percent of all taxa and numerically average 61.9 percent of all individuals (range: 20.2-96.1 percent).

Organism abundance levels (density) are considered to indicate the relative degree of environmental stress. This stress is the frequency with which the physiological tolerance limits of an organism to some environmental factor are exceeded (Menge and Sutherland, 1976). Average density levels for the Lake Erie macroinvertebrate fauna are divided into two categories (2000-3000/m^2 and 3000-4000/m^2), both of which are present in the Zone I diversity category. If greater abundance reflects a lower stress environment for the species present, then the margins of the central basin, the mouth of the Detroit River, and the region just lakeward of Sandusky Bay may be considered as more favorable environments than other parts of the lake sampled (Figure 117).

The high densities are due to the presence of large numbers of oligochaetes (Figures 118 and 119). The two other faunal components, which together with the oligochaetes, make up 92 percent, numerically, of all the benthic macroinvertebrates are the Chironomidae and the Sphaeriidae. Chironomid larvae contribute 11.8 percent toward density and Sphaeriids, 18.3 percent. In terms of their contribution to diversity, the chironomids contribute 15.2 percent and the sphaeriids, 4.5 percent. Most of the lake has average chironomid densities up to 500/m^2 with scattered regions of higher density (Figures 120 and 121). Average sphaeriid densities indicate that there are two regions of low density, the western basin and the northeastern corner of the central basin

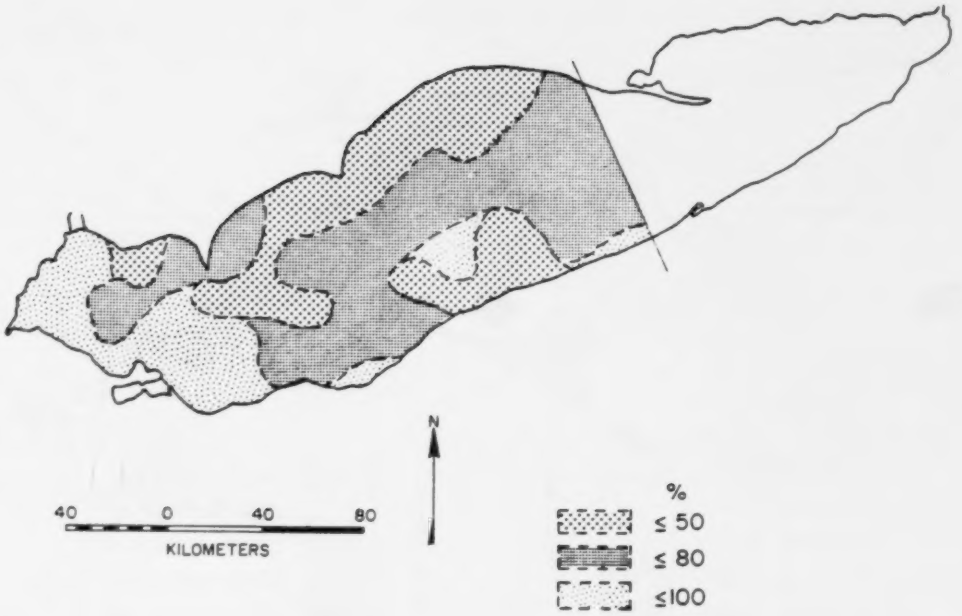

N
40
0
40
80
KILOMETERS
%
≤ 50
≤ 80
≤100

Figure 116. Average percent oligochaeta in the bottom fauna.

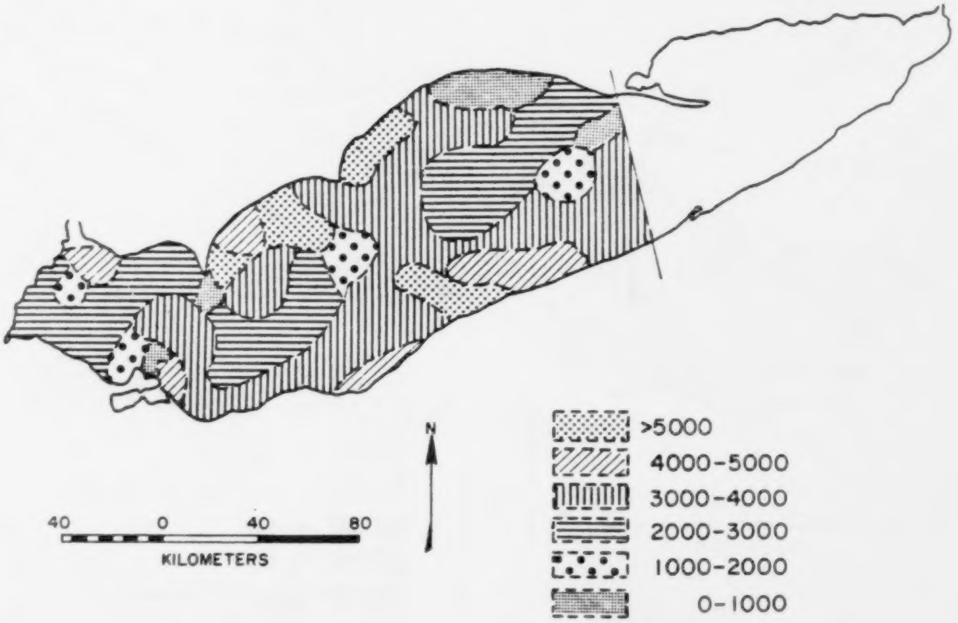

N
40
0
40
80
KILOMETERS
>5000
4000-5000
3000-4000
2000-3000
1000-2000
0-1000

Figure 117. Average benthic macroinvertebrate densities (indiv./m^2) for central and western basins of Lake Erie 1973-1974.

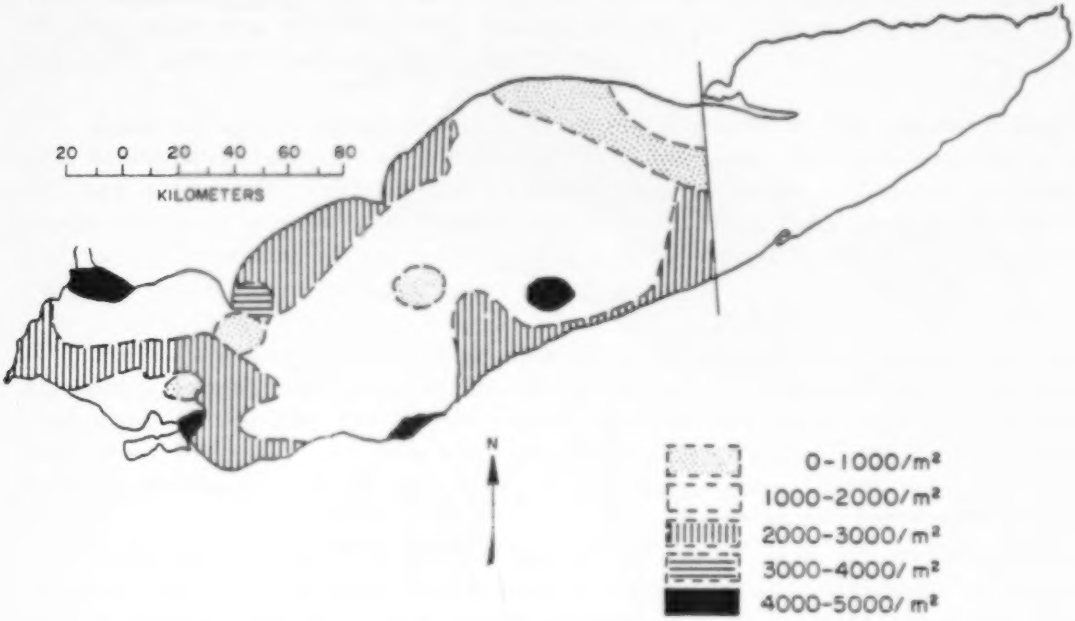

20 0 20 40 60 80
KILOMETERS
N
0-1000/m²
1000-2000/m²
2000-3000/m²
3000-4000/m²
4000-5000/m²

Figure 118. Average oligochaete density for central and western basins of Lake Erie 1973-1974.

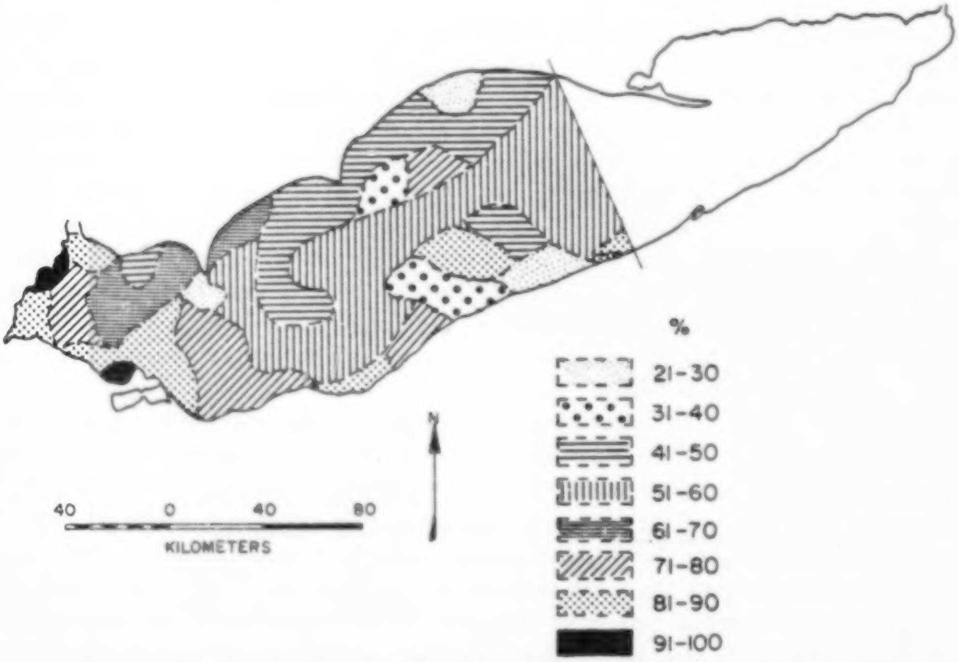

%
21-30
31-40
41-50
51-60
61-70
71-80
81-90
91-100
N
40 0 40 80
KILOMETERS

Figure 119. Average percent oligochaetes in the bottom fauna.

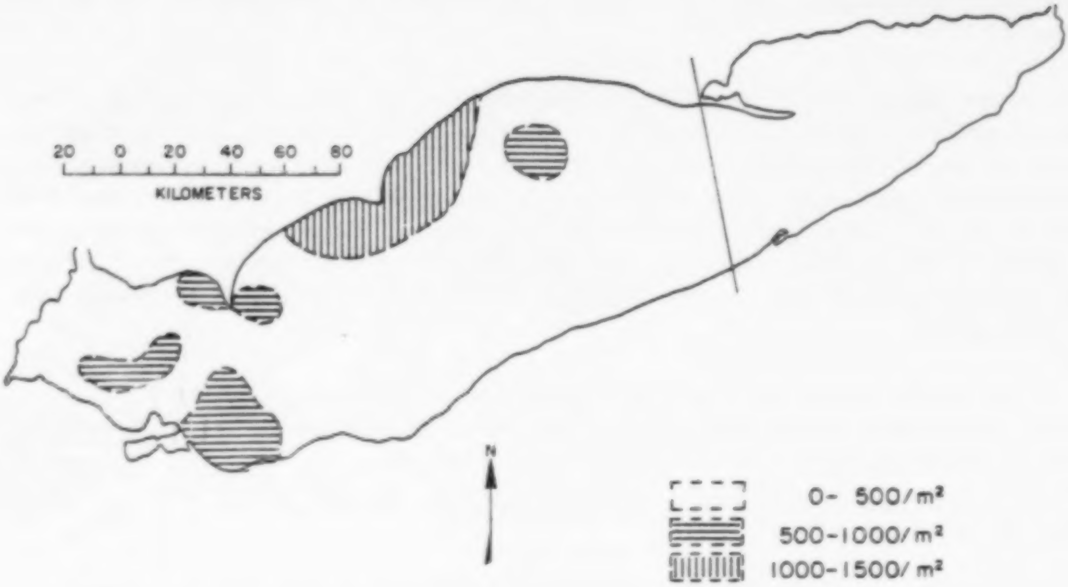

20 0 20 40 60 80
KILOMETERS
N
0- 500/m²
500-1000/m²
1000-1500/m²

Figure 120. Average chironomid density in central and western basins of Lake Erie 1973-1974.

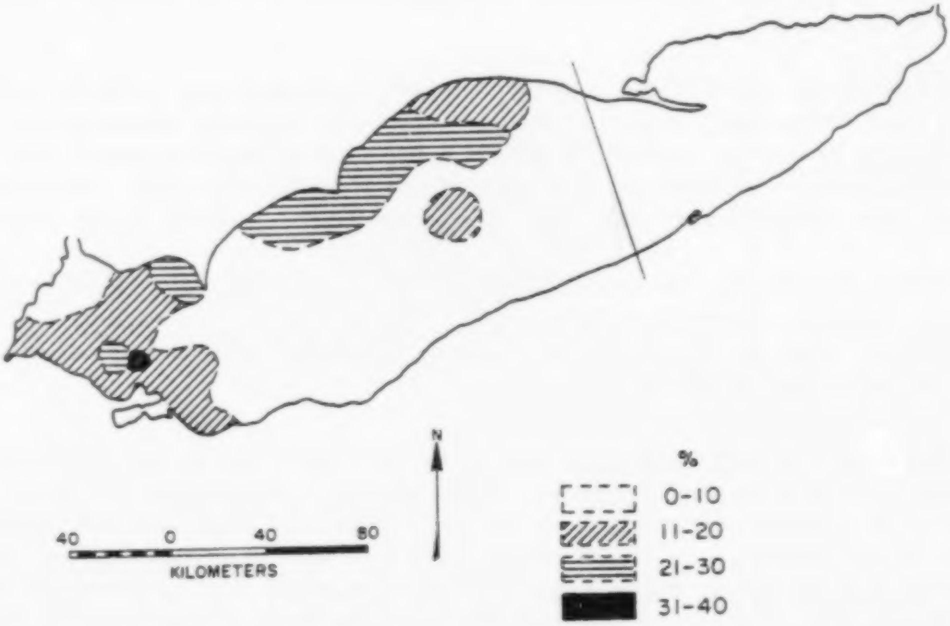

N
%
0-10
11-20
21-30
31-40
40 0 40 80
KILOMETERS

Figure 121. Average percent of chironomidae in the bottom fauna.

(Figures 122 and 123). Likewise most of the central basin has shaperiid densities in the 500-1000/m^2 range with scattered regions of higher density.

When the overall diversity is separated into its component groups, the diversities within each component may be examined and the distribuions of each individual taxa may be studies. Oligochaete diversity varies throughout the lake bottom, but most of the lake bottom has from five to eight oligochaete species (Figure 124). When referring to oligochaetes in this paper we are, for all intents, referring to the Tibificidae, although both the Lumbriculidae and the Naididae are represented (infrequently).

The most important tubificid group is the genus *Limnodrilus*, in which there are seven species. The most ubiquitous is *L. hoffmeisteri* and in order of decreasing distribution they are: *L. cervix*, *L. cervix variant*, *L. maumeensis*, *L. claperedeianus*, *L. sprialis*, and *L. udekemianus* (Figure 125).

In the western basin, the *Limnodrilus* species are the dominant oligochaetes. In the central basin, *Peloscolex ferox* and *P. multisetosus* become dominant. *P. ferox* oftentimes is the only oligochaete in some of the stations. Both *Peloscolex* species are widely distributed throughout the central basin and in large areas of the western basin (Figure 126).

Relative to these two genera, the other oligochaete species are much less important, except locally, and less broadly distributed. *Branchiura sowerbyi* seems to be limited to the western basin and to the southwestern corner of the central basin (Figure 126). However, it has been collected at one site along the north central basin margin.

Other tubificids, including *Potamothrix moldaviensis*, *P. vejdovskyi*, *Tubifex tubifex*, *Ilyodrilus templetoni*, *Aulodrilus americanus*, *A. Limnobius*, and *A. pluriseta* are scattered throughout both basins as are the Naididae (Figure 127).

Potamothrix moldaviensis seems to be found along the northern and southern central basin margins. *Potamothrix vejdovskyi*, however, is found in a number of areas. It is very probable that the distribution of these two species is much more widespread. *Tubifex tubifex* is found scattered along the margins of both basins, but is probably found throughout the western basin and the western half of the central basin (Figure 127). *Ilyodrilus templetoni* has been found only off the tip of Pelee Point. *Aulodrilus americanus* and *A. limnobius* are found in both basins, but so far have been collected from only three stations (Figure

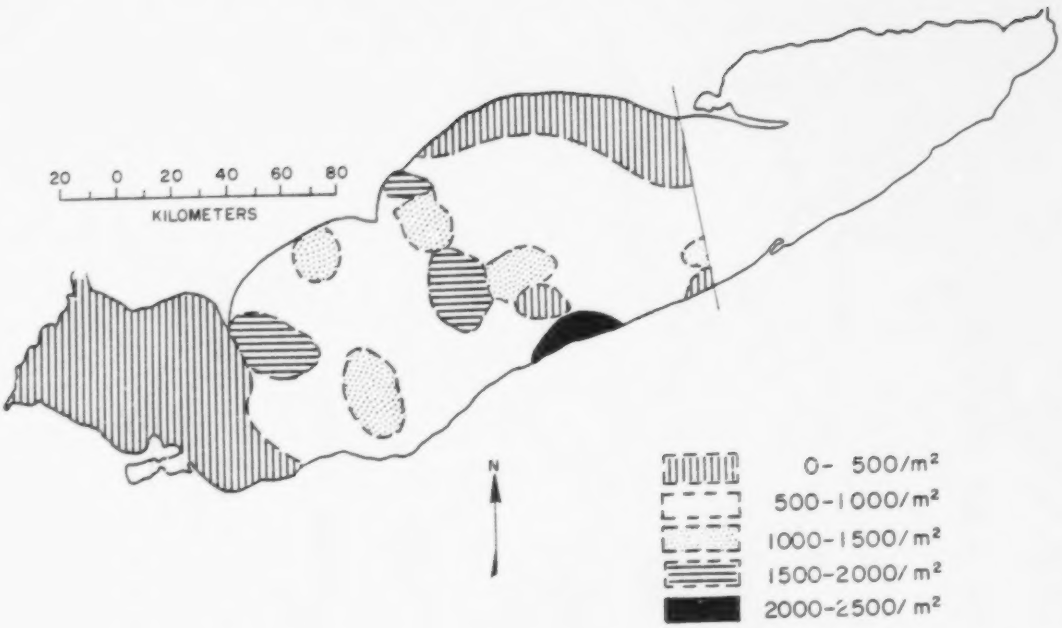

20 0 20 40 60 80
KILOMETERS
N
0- 500/m²
500-1000/m²
1000-1500/m²
1500-2000/m²
2000-2500/m²

Figure 122. Average sphaeriid density in the central and western basins of Lake Erie 1973-1974.

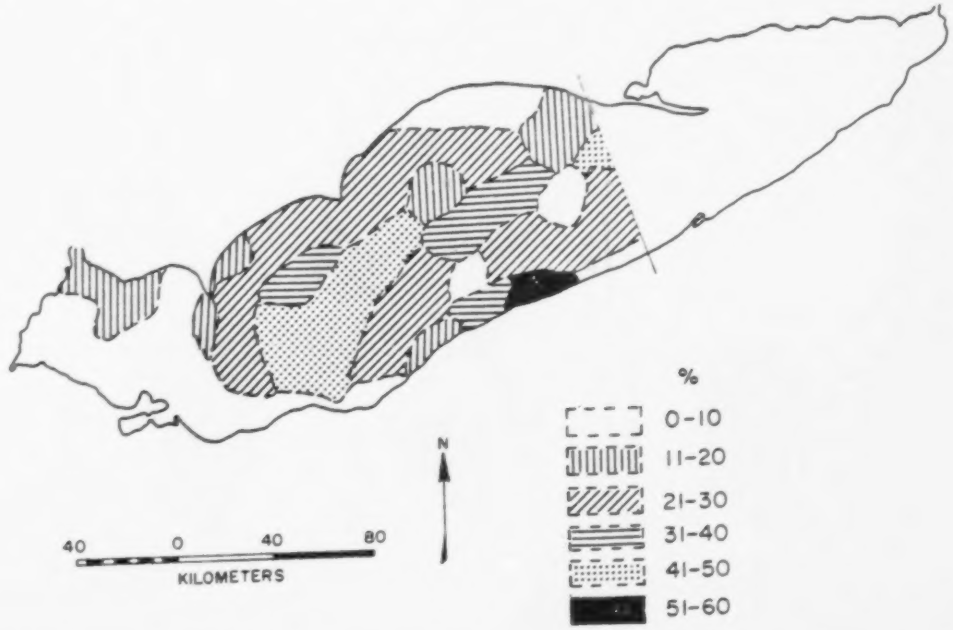

%
0-10
11-20
21-30
31-40
41-50
51-60
40 0 40 80
KILOMETERS
N

Figure 123. Average percent of sphaeridae in the bottom fauna.

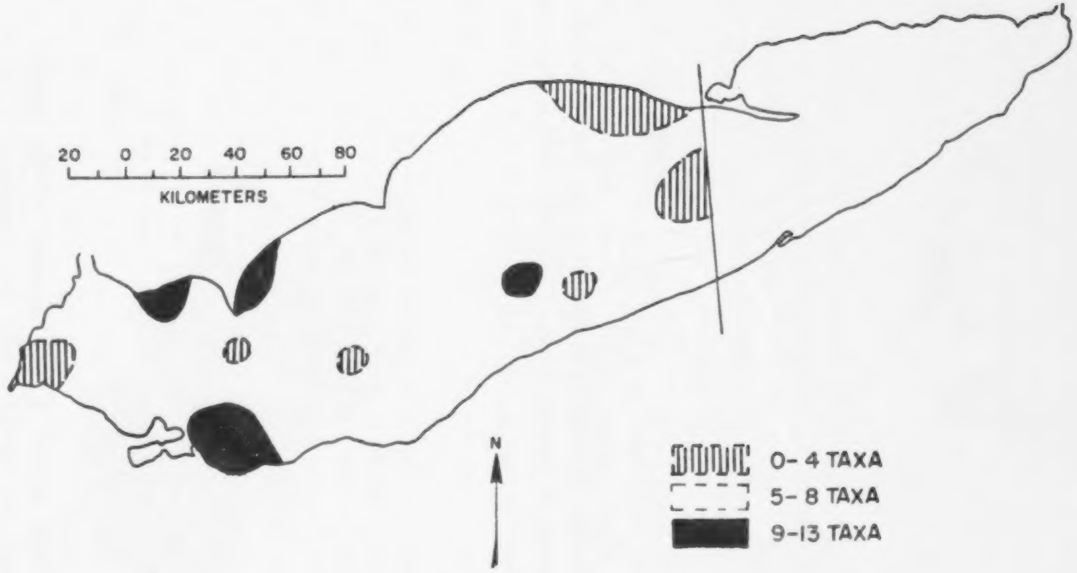

20 0 20 40 60 80
KILOMETERS
N
0- 4 TAXA
5- 8 TAXA
9-13 TAXA

Figure 124. Average oligochaete diversity in the central and western basins of Lake Erie 1973 - 1974.

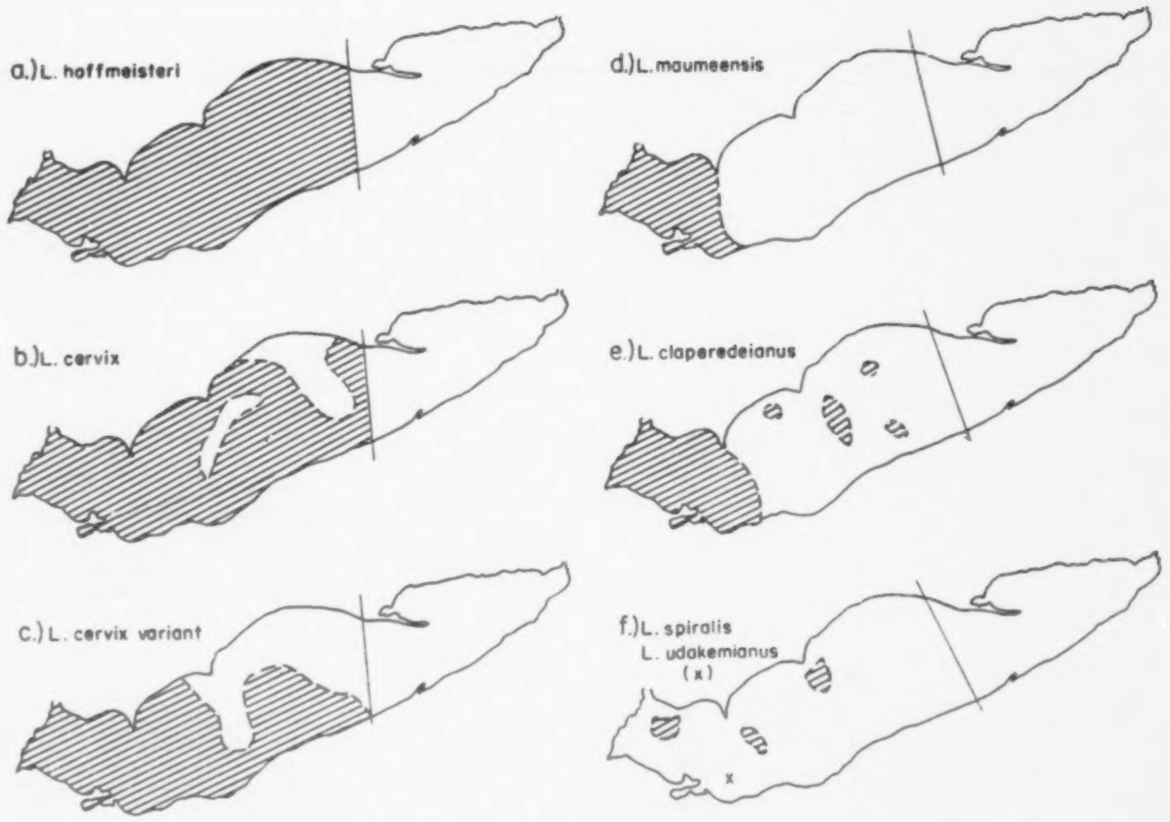

a.) L. hoffmeisteri
b.) L. cervix
c.) L. cervix variant
d.) L. maumeensis
e.) L. claperedeianus
f.) L. spiralis
L. udakemianus
(x)
x

Figure 125. Distribution of *Limnodrilus* species in the central and western basins of Lake Erie 1973-1974.

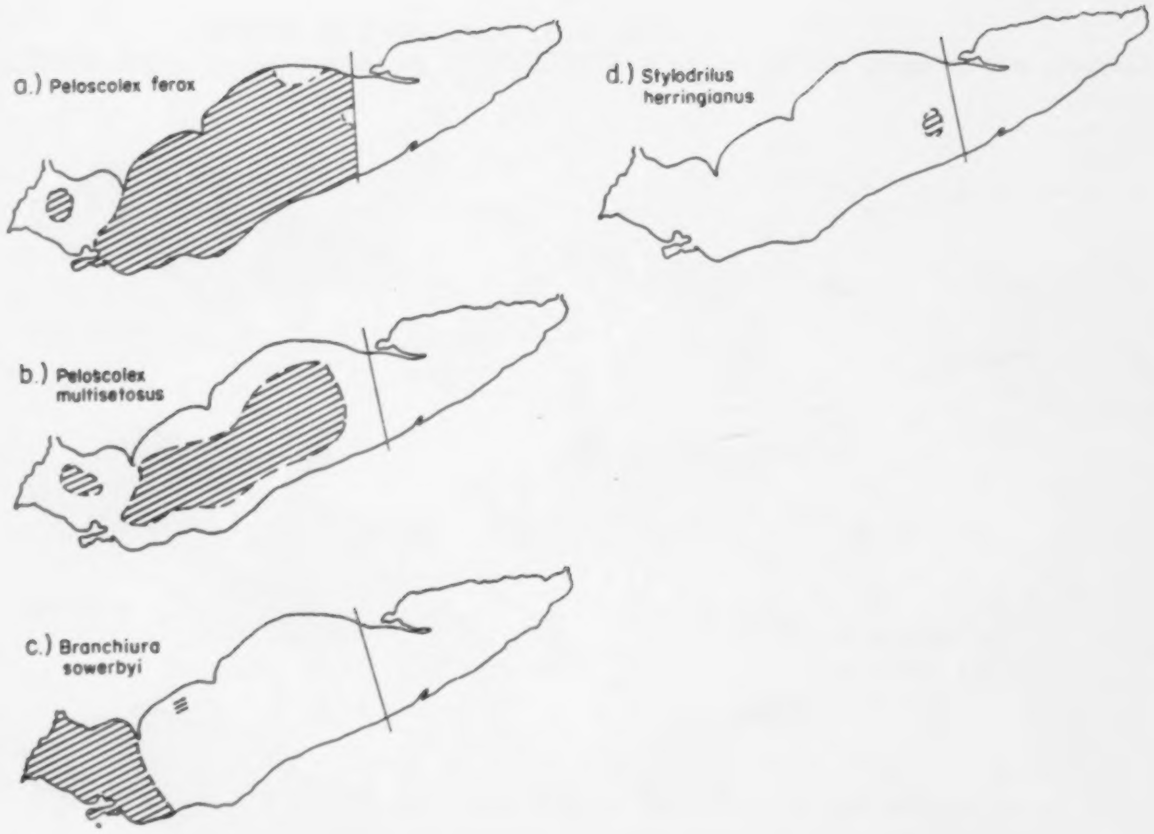

a.) Peloscolex ferox
b.) Peloscolex multisetosus
c.) Branchiura sowerbyi
d.) Stylodrilus herringianus

Figure 126. Distribution of Oligochaete species in the central and western basins of Lake Erie 1973-1974.

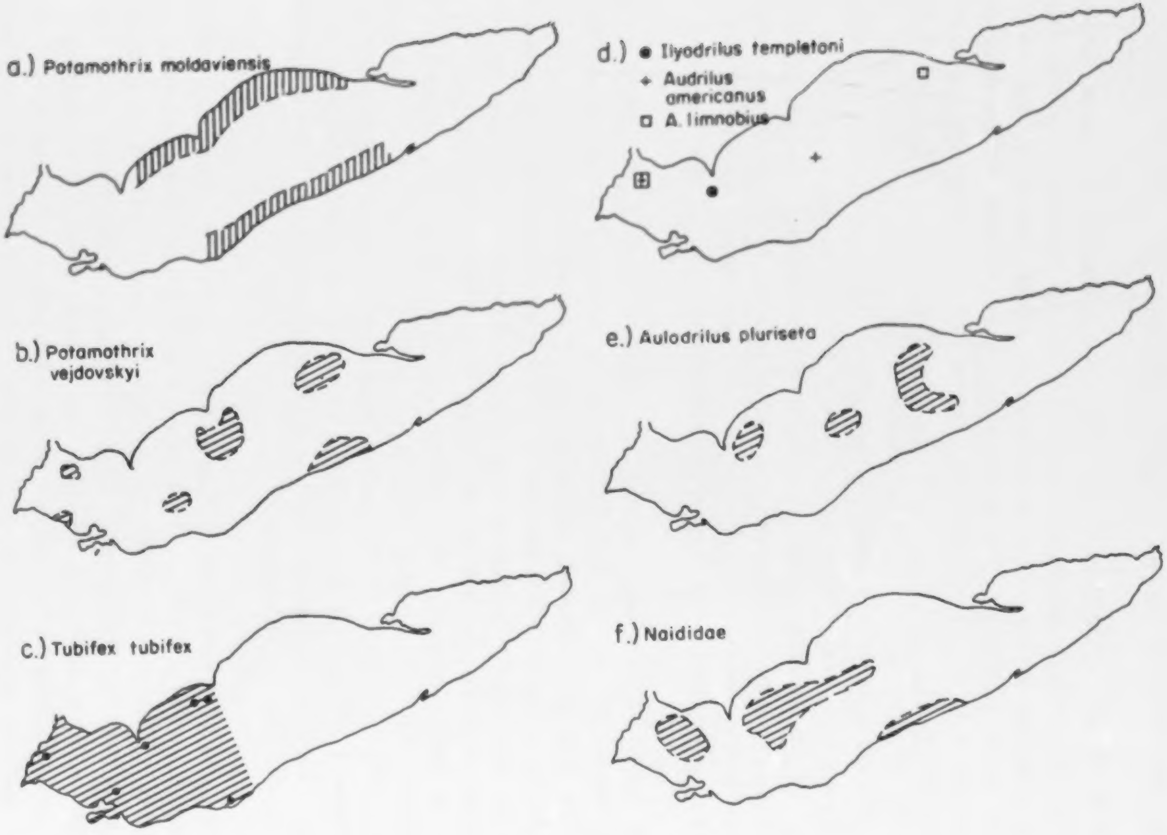

a.) Potamothrix moldaviensis
b.) Potamothrix vejdovskyi
c.) Tubifex tubifex
d.) ● Ilyodrilus templetoni
+ Audrilus americanus
□ A. limnobius
e.) Aulodrilus pluriseta
f.) Naididae

Figure 127. Distribution of Oligochaete species in the central and western basins of Lake Erie 1973-1974.

127). *Aulodrilus pluriseta* has been found in three regions of the central basin (Figure 127).

The lumbriculid, *Stylodrilus herringianus*, generally considered to be intolerant of enriched conditions, is limited to the far east and middle region of the central basin (Figure 126).

Brinkhurst el al. (1968) divided the oligochaetes of Lake Erie into three associations which approximated the three basins. They reported that the oligochaetes were very abundant at river mouths and in the western basin with *Limnodrilus hoffmeisteri* being the most abundant species. Found with *L. hoffmeisteri* were other *Limnodrilus* species (*L. claperedeianus*, *L. cervix*, and *L. maumeensis*). *Tubifex tubifex* was found only at the Detroit river mouth. Further out into the western basin, they found *Aulodrilus* and *Potamothrix* species together with *Branchiura sowerbyi* and *Peloscolex ferox* or *multisetosus*. The central basin had *P. ferox* as its most abundant oligochaete. In addition *Bothrioneurum vejdovskyanum*, *Ilyodrilus templetoni*, *Potamothrix*, and *Aulodrilus* species were found. *Aulodrilus* species were widely distributed and of greatest abundance in the shallower regions of the eastern basin.

The next most important faunal component is the Mollusca, represented by 16 taxa, of which the Sphaeriidae are the most important. The shpaeriids are distributed ubiquitously throughout both basins with the density pattern described earlier. The Unionidae are limited to the open waters of the western basin and occur in relatively low numbers. The Gastropoda contribute the most toward mollusc diversity with nine taxa. Most of these snails, however, are limited to the western basin and the southern margin of the central basin (Figure 128). *Valvata sincera* is the most widely distributed snail. It occurs throughout both basins but doesn't occur in the middle reaches of the central basin (Figure 128). The distribution of *V. sincera* represents the maximum distribution of all the Gastropoda.

The gastropod distribution in Lake Erie is most probably due to oxygen processes in the lake. The snails collected were almost exclusively prosobranch (internal gill) types which must utilize dissolved oxygen in the water for respiration. Although these organisms can be found at oxygen concentrations as low as 2 ppm (Hart and Fuller, 1974) a complete lack of oxygen for such time periods as in the Lake Erie central basin during summer is prohibitive. During the mixed well-oxygenated part of the year, there appears to very little immigration to these areas. *Valvata sincera* seems to be the only snail which has an extended range well into the central basin, but it too is not found in the middle reaches of the central basin. Snail abundance levels in the central basin are very low (10-20/m^2).

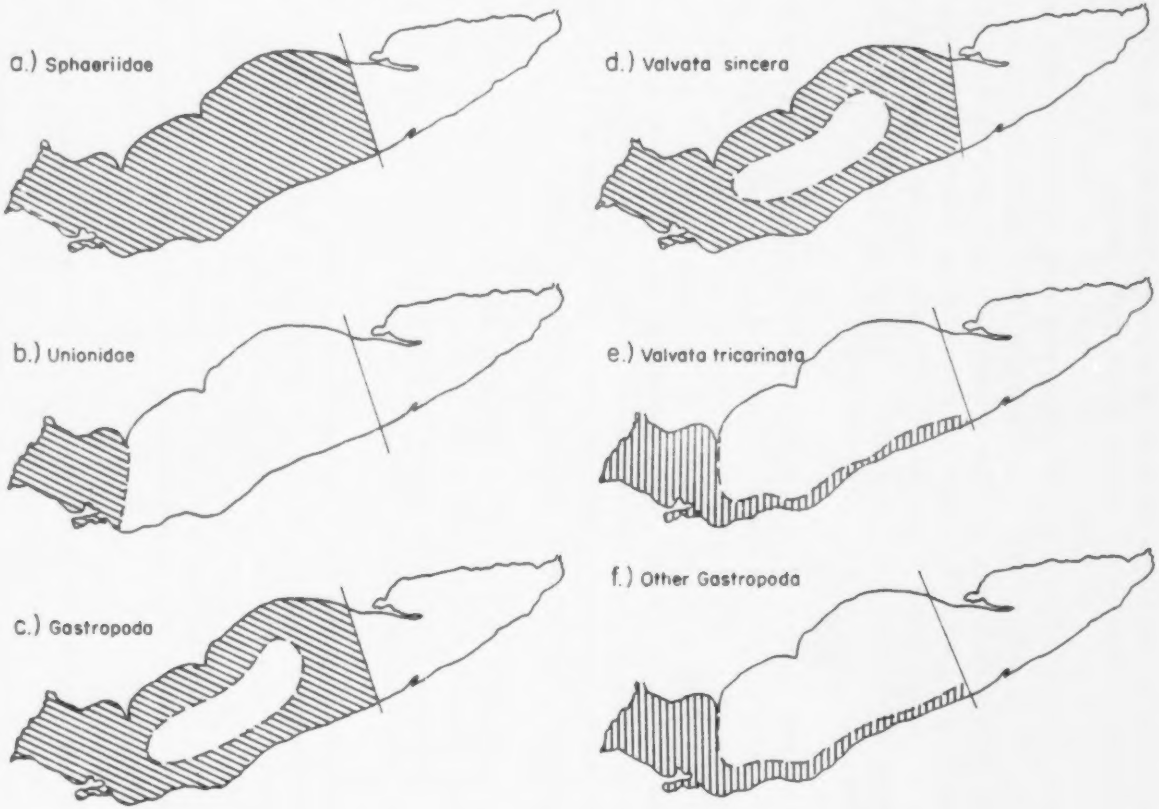

a.) Sphaeriidae
b.) Unionidae
c.) Gastropoda
d.) Valvata sincera
e.) Valvata tricarinata
f.) Other Gastropoda

Figure 128. Distribution of mollusca in the central and western basins of Lake Erie 1973-1974.

Unionid clams are likewise limited in their distribution. This study found their abundance to be very low in the open waters (1 or $2/m^2$) when collected. However, the frequency with which they were collected was very low (maximum of 4 stations/cruise - usually 2 stations/cruise). The distribution of the unionids and their abundance is probably due to several factors; the most important of which are probably dissolved oxygen and siltation (which may occur synergistically).

Following the Mollusca in importance are the Chironomidae with 10 taxa. The density levels of the chironomids have been examined earlier and will not be discussed here. The most common chironomid is *Chironomus plumosus*, and in order of decreasing distribution they are: *Procladius* sp., *Chironomus riparius*, *Micropsectra* sp., *Coelotanypus* sp., *Chironomus (Cryptochironomus)* sp., *Microtendipes* sp., *Metriocnemus* sp., and *Tanytarsus* sp. (Figure 129).

Throughout both basins *C. plumosus* and *Procladius* sp. are the dominant chironomids. In the western basin, *Coelotanypus* sp. and *C.* (*Cryptochironomus*) sp. are significant members of the chironomid assemblage. In the central basin these two genera become insignificant except near the basin margins. *Coelotanypus* sp. is represented along the southwestern edge of the central basin and *C.* (*Cryptochironomus*) sp., along the northwestern margin of the central basin and the southern margin off Fairport Harbor and Conneaut (Figure 129).

Along the northern shore, *Micropsectra* sp. and *Tanytarsus* sp. are well distributed (Figure 129). Rare or uncommon genera include *Microtendipes* sp., *Tanypus* sp., and *Metriocnemus* sp., which are found along the margins of the central basin (Figure 129).

The distributions of the various taxa comprising relatively minor positions in the benthic fauna are shown in Figure 130. These faunal units contribute 15 taxa toward diversity, but only eight percent numerically toward density. These fauna include the six leech species, two amphipod species, one isopod species, one opposum shrimp species, one polychaete species, one coelenterate, two flatworm families, and one genera of caddisfly.

High sediment organic content in bodies of water, such as Lake Erie (Figure 131) are accompanied by a high oxygen demand by these sediments and their microflora. In shallow waters this demand may be met at the mud-water interface by water containing dissolved oxygen being driven downwards by wind action. The dissolved oxygen content of the bottom water at the interface, however, will be lowered. In waters deep enough to develop a summer hypolimnion, wind circulation

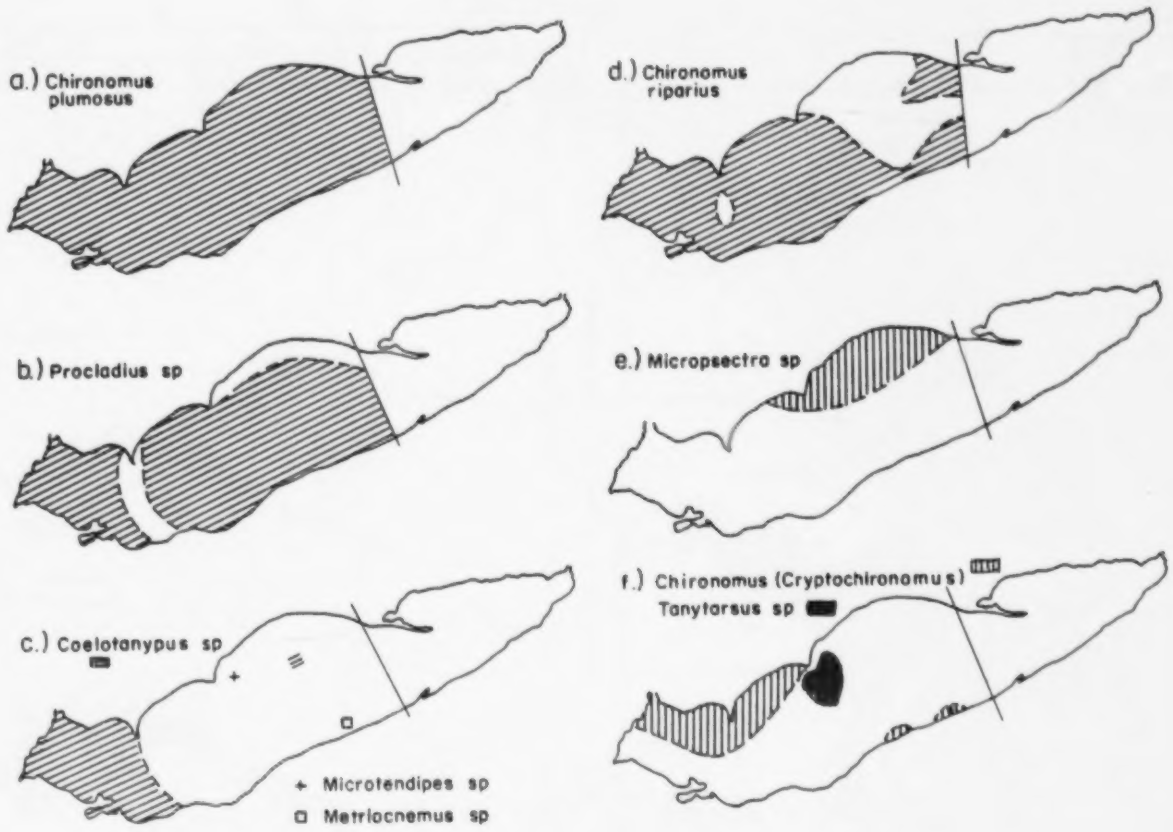

a.) Chironomus plumosus
b.) Procladius sp
c.) Coelotanypus sp ▤
+ Microtendipes sp
□ Metriocnemus sp
d.) Chironomus riparius
e.) Micropsectra sp
f.) Chironomus (Cryptochironomus) ▥
Tanytarsus sp ■

Figure 129. Distribution of chironomidae in the central and western basins of Lake Erie 1973-1974.

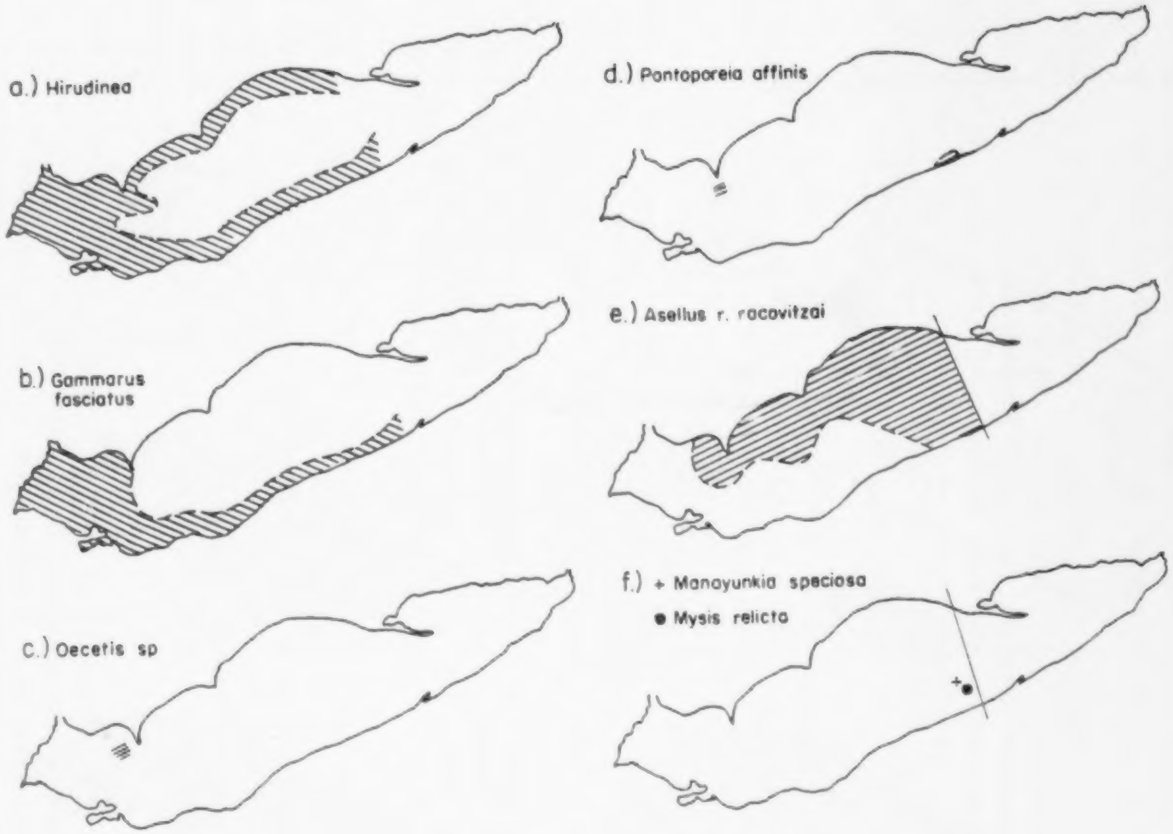
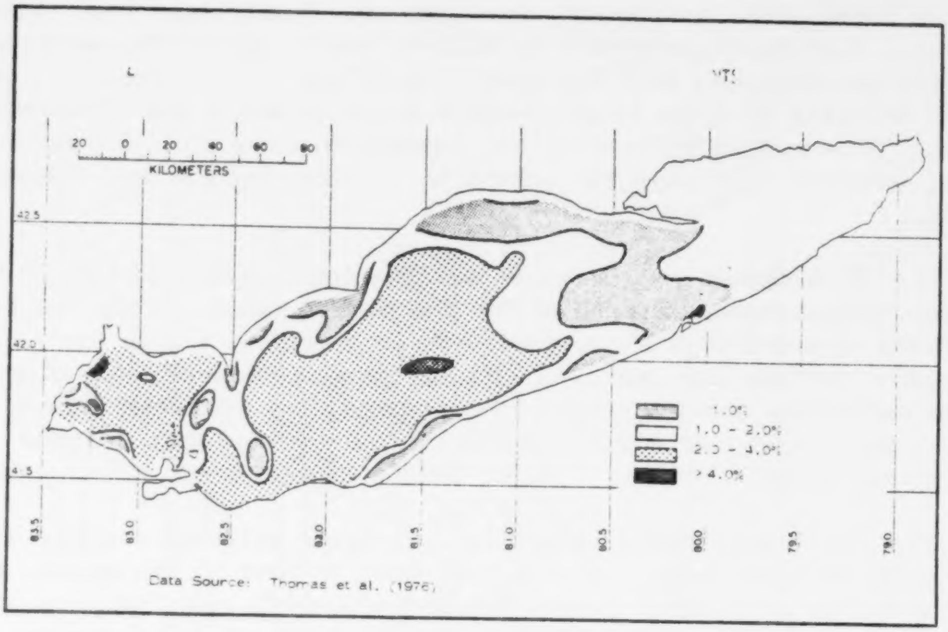

a.) Hirudinea
b.) Gammarus fasciatus
c.) Oecetis sp
d.) Pontoporeia affinis
e.) Asellus r. racovitzai
f.) + Manayunkia speciosa
● Mysis relicta

Figure 130. Distribution of minor elements in the central and western basins of Lake Erie 1973-1974.


20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
1.0%
1.0 - 2.0%
2.0 - 4.0%
> 4.0%

Data Source: Thomas et al. (1976)

Figure 131. Distribution of organic carbon in surficial sediments (% dry weight).

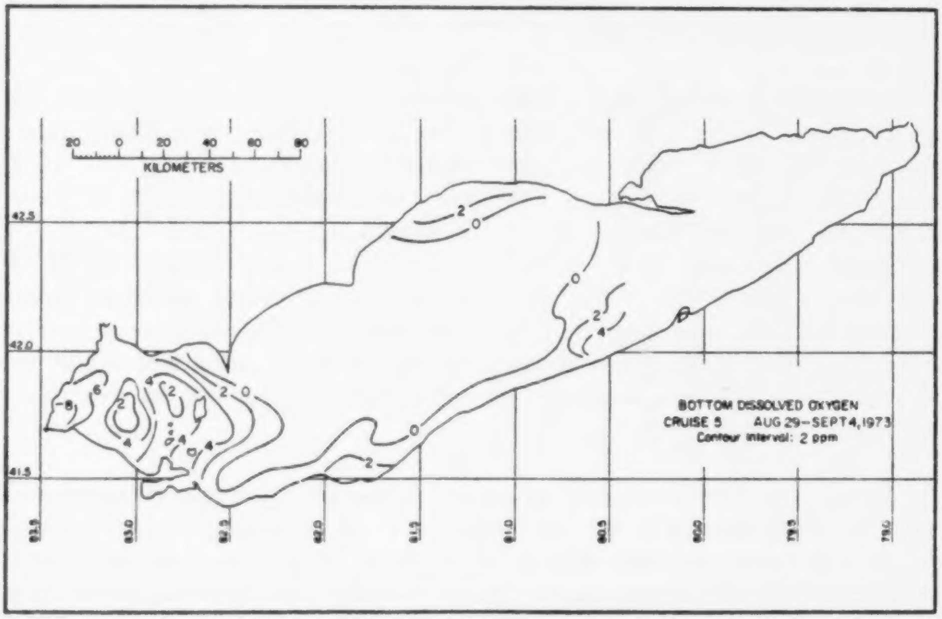

20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
2
0
2
4
8
6
4
2
4
2
0
0
2
BOTTOM DISSOLVED OXYGEN
CRUISE 5 AUG 29–SEPT 4, 1973
Contour interval: 2 ppm

Figure 132. Bottom dissolved oxygen, cruise 5, August 29-September 4, 1973.

is insufficient to renew the hypolimnetic oxygen stock. As a result, unless some other mechanism operates, the hypolimnion may become anoxic. For the hypolimnion to become anoxic during the summer, it must be relatively thin and have a sufficient oxygen depletion rate as in the case in Lake Erie's central basin (Blanton and Winklhofer, 1972). Thermal stratification may persist in Lake Erie for up to 110 days, which is sufficient for anoxia to develop (Dobson and Gilbertson, 1972).

During summer stratification the dissolved oxygen content of the bottom waters becomes critical for the bottom fauna. Only the faunal elements tolerant of low oxygen levels or complete anoxia for relatively long time periods can survive. Faunal groups generally found under these conditions are the tubifid oligochaetes, the sphaeriid clams, and the midge larvae (particularly those of Chironomus sp.). These are the major faunal elements of Lake Erie's central basin.

The survival of these organisms and their relative success in areas exhibiting anoxic conditions is due at least in part to the ability of these organisms to shift their metabolism from aerobic respiration to anaerobic respiration. Anaerobic respiration involves obtaining energy by splitting carbohydrates into lactic acid, fatty acids or mixtures of the two. The process stops at this point. Aerobic respiration is similar except that the splitting of the carbohydrates is carried further to produce carbon dioxide and water.

In 1973 the central basin was anoxic to its greatest extent by late August (Figure 132). At this time the average bottom fauna density for the central basin was $3235/m^2$ with an average diversity of seven. These values were the lowest for the 1973 sampling year. Prior to this time the central basin densities averaged 4120 and $5457/m^2$ during June and July 1973, while diversities were 10 and 9 for the same period (Table 75). As the season progressed towards anoxia in the central basin, changes in both density and diversity were noted (Figures 133 and 134). Upon the return of oxic conditions there was also an increase in the average density but no change in the diversity for the 1973 year.

In 1974, the bottom went anoxic in the southwestern edge of the central basin at stations 51 and 46 about 12 August, while maximum anoxia extent was reached about 26 August (Figures 135 and 136). Lowered benthic densities were observed for the 26 August-7 September cruise. In the central basin density levels as well as diversity levels dropped significantly in June (Figures 133 and 134). Recovery occurred during July but dropped during anoxia. June is the month when a large emergence of midges occurs, and this may be the primary cause for the density and diversity drop.

TABLE 75. COMPARISON OF DENSITY AND DIVERSITY (TAXA NUMBER/M^2) FOR THE WESTERN AND CENTRAL BASINS, 1973 - 1974

	1973				1974				
Cruise Number	1	2	5	7	2	4	6	8	10
Average Density									
Central Basin	4120	5457	3225	3689	4338	1865	3910	3471	3409
Western Basin	5460	3805	3615	2337	1618	674	1443	2592	2017
Central and Western Average	4494	5551	3323	3248	3250	4480	3135	3202	3000
Average Diversity									
Central Basin	10	9	7	7	9	7	9	9	9
Western Basin	13	9	11	6	10	7	7	10	12
Central and Western Average	10	9	8	7	9	7	8	10	9

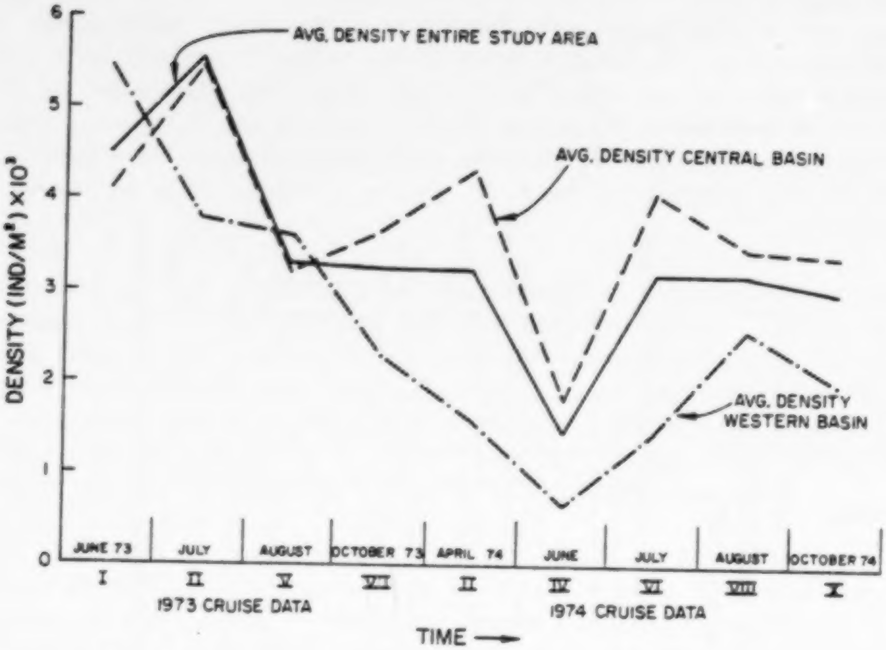


Figure 133. Average density changes in central and western basins (1973-1974) during ice-free months.

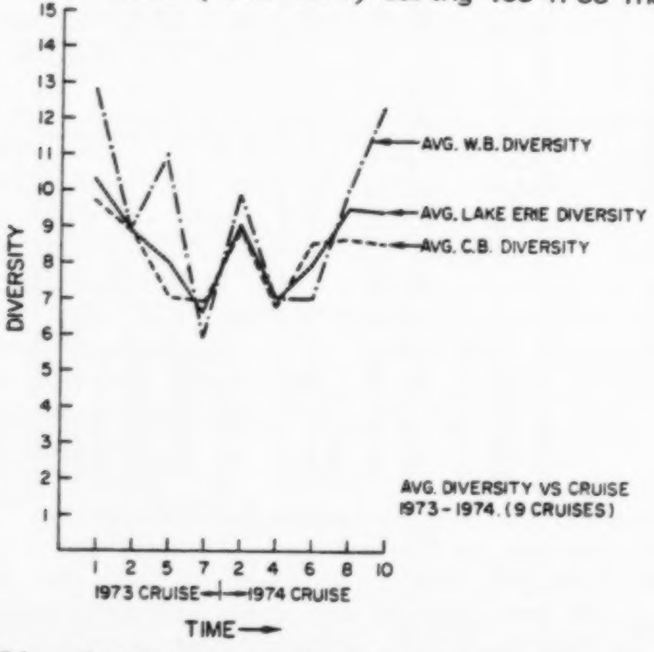


Figure 134. Average diversity changes in central and western basins (1973-1974.

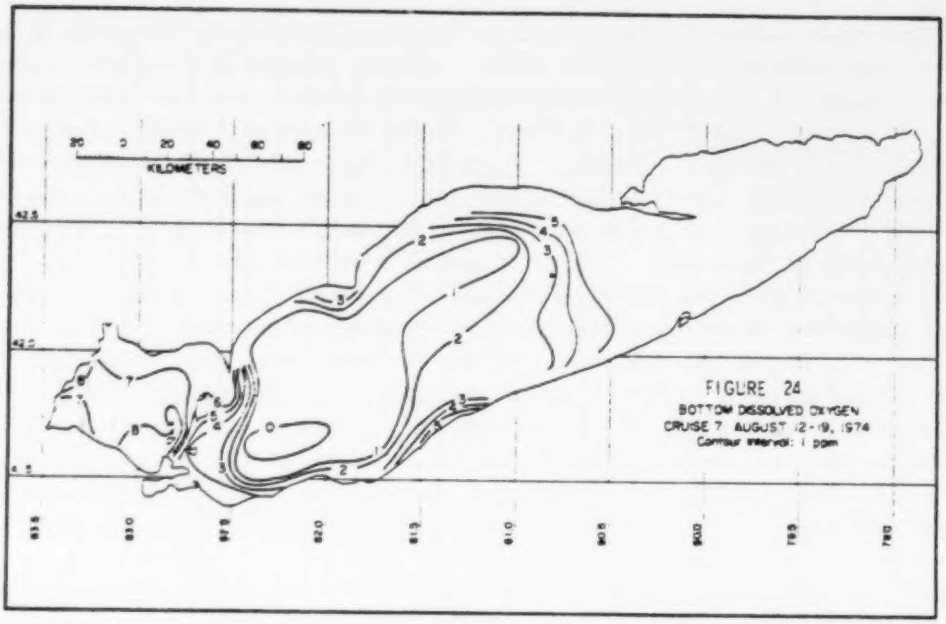

20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
0
1
2
3
4
5
6
7
8
FIGURE 24
BOTTOM DISSOLVED OXYGEN
CRUISE 7 AUGUST 12-19, 1974
Contour interval: 1 ppm

Figure 135. Bottom dissolved oxygen, cruise 7, August 12-19, 1974.

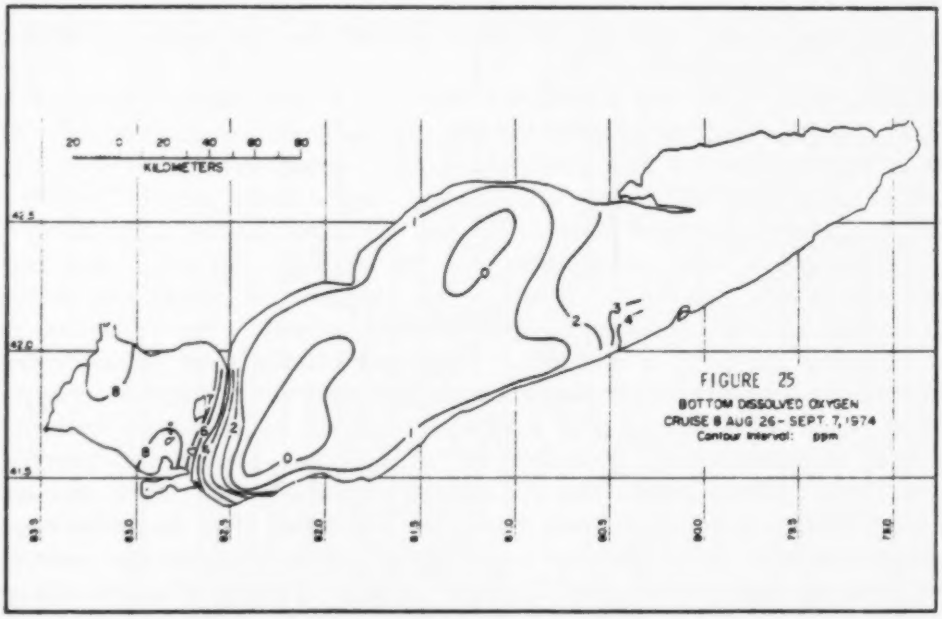

20 0 20 40 60 80
KILOMETERS
42.5
42.0
41.5
83.5
83.0
82.5
82.0
81.5
81.0
80.5
80.0
79.5
79.0
0
1
2
3
4
6
7
8
FIGURE 25
BOTTOM DISSOLVED OXYGEN
CRUISE 8 AUG 26 - SEPT. 7, 1974
Contour interval: ppm

Figure 136. Bottom dissolved oxygen, cruise 8, August 26-September 7, 1974.

HISTORICAL TRENDS

The open water fauna of Lake Erie has definitely undergone a number of changes since at least 1930. Prior to and during the 1930's, the bottom fauna of the western basin was dominated by the burrowing mayfly, Hexagenia (Carr and Hiltunen, 1965; Chandler, 1963; Shelford and Boesel, 1942, Wright, 1955). Data for the central basin bottom fauna was not available for this time period. Other taxanomic groups were relatively unimportant in comparison, although the tubificid oligochaetes became very important in river mouths and harbors (Table 76). Wright (1955) categorized the western basin into several pollution categories based upon the number of tubificid oligochaetes present. This was an arbitrary scale which seemed proper for the time in the western basin. Light pollution was at oligochaete densities of 100 to 999/m^2. Moderate pollution was at densities 1000-5000/m^2. Heavy pollution was at oligochaete densities greater than 5000/m^2. Most of the western basin at this time was considered unpolluted, while the mouths of the Maumee, Raisin and Detroit Rivers were considered polluted (Figure 137).

From 1930 through 1961, Carr and Hiltunen (1965) reported that: (1) Hexagenia had decreased to less than one percent of its previous abundance, (2) oligochaetes had increased ninefold in density, (3) the extent of areas defined as polluted by Wright/s index had increased, (4) chironomid densities had increased four times, (5) sphaeriid levels had magnified twice, and (6) the snail densities increased sixfold.

Britt (1955) reported a drastic decline in the mayfly population during 1953 due to thermal stratification and bottom water oxygen depletion in the western basin. The population recovered by by 1959 had been very much reduced (Beeton, 1961). By 1965, Britt et al. (1973) considered Hexagenia almost extinct in the western basin. In 1973 and 1974 no Hexagenia was collected. In the spring, summer and fall of 1963 and 1964, the U.S. Public Health Service conducted surveys of the bottom fauna of Lake Erie (FWPCA, 1968). This survey was also conducted in 1967 and 1968. They concluded that most of the western and central basins were characterized by a lack of the pollution sensitive scud populations and a preponderance of pollution tolerant species of sludgeworms, bloodworms, fingernail clams and nematodes (Figure 138). They identified 34 species in the lake. The survey conducted during the 1963-1964 seasons indicated that the average bottom fauna density was 1666/m^2. Average densities for the western and central basins were 1164 and 1861/m^2, respectively (Figure 139).

The 1973 and 1974 sampling seasons discussed here indicate average bottom faunal densities to be 3409/m^2. Average densities for the western and central basins are 2612 and 3719/m^2, respectively, double the levels found in 1963 and 1964 (Figure 140).

TABLE 76. LAKE ERIE WESTERN BASIN BOTTOM FAUNA
1929-1930 - WRIGHT (1955)

	Island Region		Maumee Bay - Toledo Harbor		Portage River Area	
	1929	1930	1929	1930	1929	1930
Amnicola	11	21	50	14		
Bithynia			31	5		
Chironomidae	58	21	156	98	18	?
Gastropoda						
Goniobasis						
Hexagenia	283	510	22	63	0	few
Hirudinea	24	14	59	76		
Sphaeriidae	23	14	187	332		
Trichoptera	18	1	72	0		
Tubificidae	12	5	31	504	19	0
Valvata	9	1	106	16		

	Detroit River	Raisin River Section		
	1930	1929	1930	
Amnicola		10	88	
Bithynia				
Chironomidae	9	107	55	
Gastropoda	81			
Goniobasis		18	18	
Hexagenia	0	57	8	
Hirudinea		7	3	
Sphaeriidae	374	125	46	
Trichoptera		78	8	
Tubificidae	1500	21	104	
Valvata		4	1	

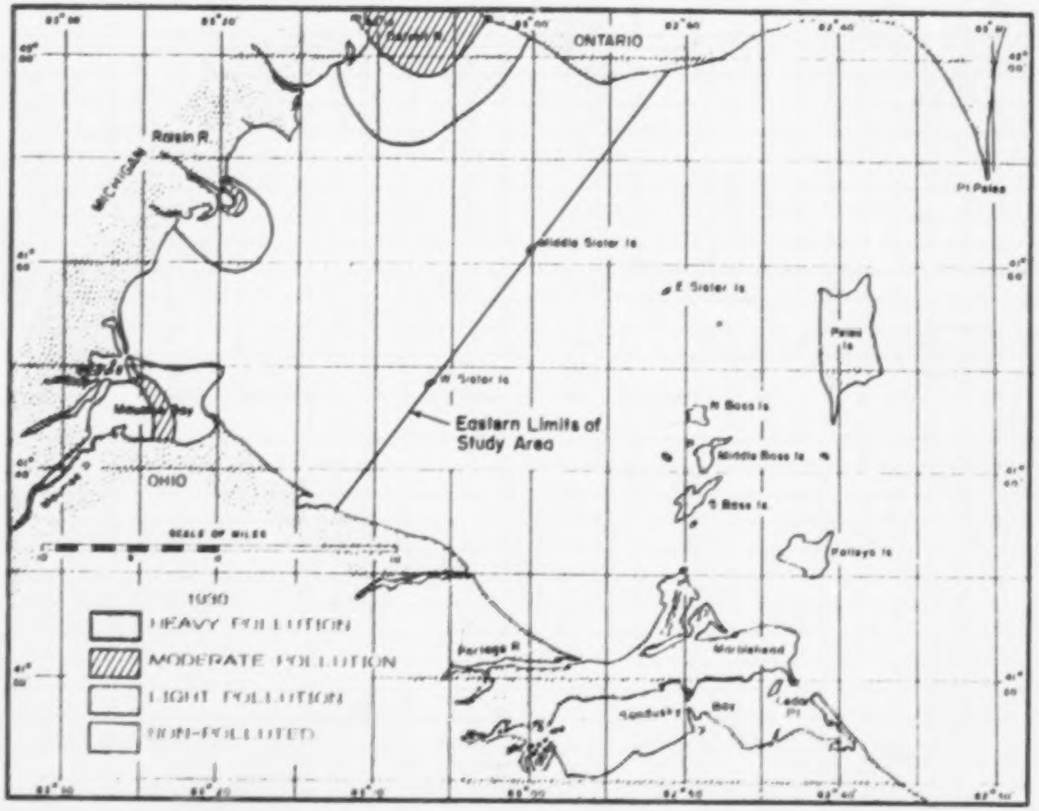
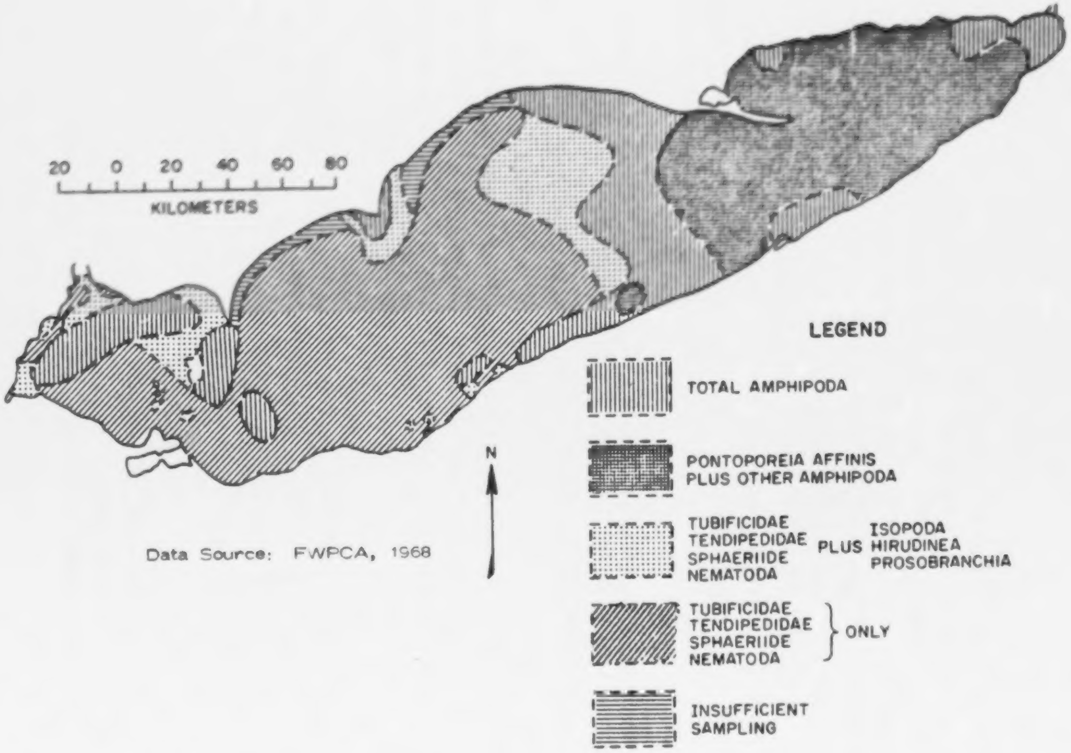
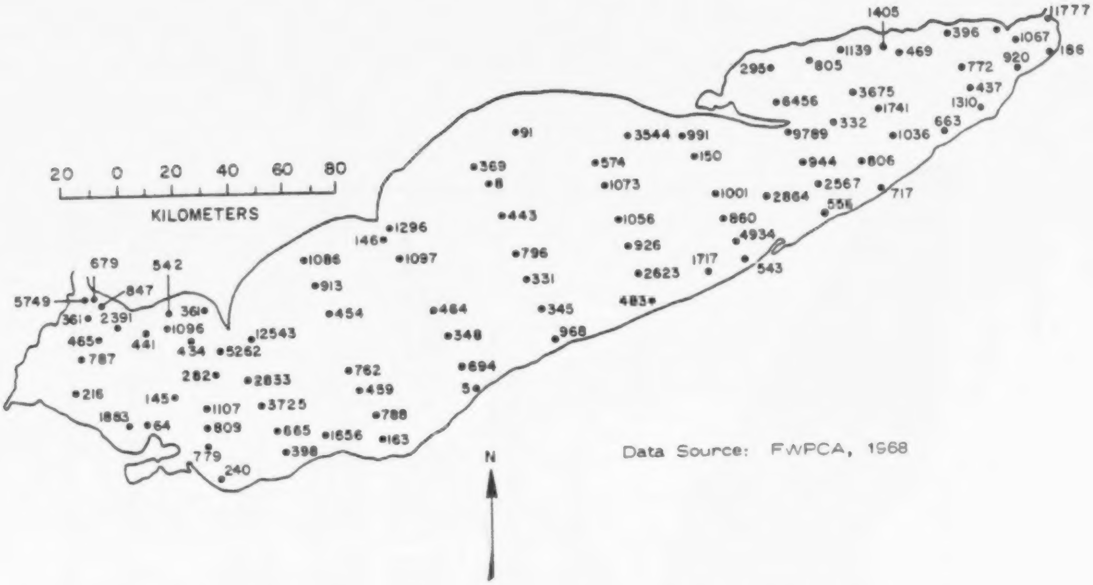

ONTARIO
Raisin R.
MICHIGAN
Middle Sister Is
E. Sister Is
W. Sister Is
Eastern Limits of Study Area
Pelee Is
Pt Pelee
N Bass Is
Middle Bass Is
S Bass Is
Kelleys Is
Maumee Bay
OHIO
SCALE OF MILES
Portage R.
Marblehead
Sandusky Bay
Cedar Pt
1930
HEAVY POLLUTION
MODERATE POLLUTION
LIGHT POLLUTION
NON-POLLUTED

Figure 137. Extent of organic pollution indicated by tubificid index (Wright, 1955).


20 0 20 40 60 80
KILOMETERS
N
LEGEND
TOTAL AMPHIPODA
PONTOPOREIA AFFINIS PLUS OTHER AMPHIPODA
TUBIFICIDAE TENDIPEDIDAE SPHAERIIDE NEMATODA PLUS ISOPODA HIRUDINEA PROSOBRANCHIA
TUBIFICIDAE TENDIPEDIDAE SPHAERIIDE NEMATODA ONLY
INSUFFICIENT SAMPLING

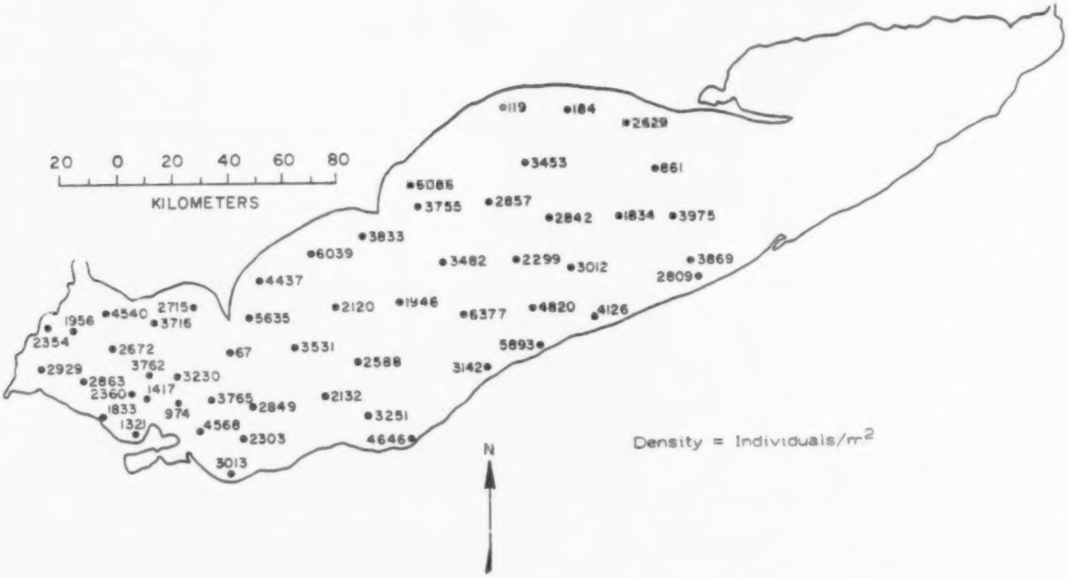
Data Source: FWPCA, 1968

Figure 138. Lake Erie benthic population distribution 1963-1964.


20 0 20 40 60 80
KILOMETERS
N
1405
11777
396
1067
1139
469
920
186
295
805
772
437
6456
3675
1310
1741
332
663
9789
1036
3544
991
91
150
369
8
574
1073
944
806
2567
717
1001
2864
556
443
1056
860
4934
1296
146
1086
1097
796
926
1717
543
679
542
913
331
2623
5749
847
454
464
345
483
361
2391
361
1096
12543
348
968
465
441
434
5262
787
694
762
282
2833
5
459
216
145
1107
3725
788
1883
64
809
865
1656
163
779
398
240

Data Source: FWPCA, 1968

Figure 139. Lake Erie benthic population distribution 1963-1964.


20 0 20 40 60 80
KILOMETERS
N
119
184
2629
3453
861
5086
3755
2857
2842
1834
3975
3833
6039
3482
2299
3012
3869
2809
4437
2715
1956
4540
3716
5635
2120
1946
6377
4820
4126
2354
2672
67
3531
5893
2929
3762
2588
3142
2863
3230
2360
1417
3765
2849
2132
1833
974
3251
1321
4568
2303
4646
3013

Density = Individuals/m^2

Figure 140. Average density Lake Erie benthic populations 1963-1964.

If Wright's (1955) pollution index utilizing the oligochaetes was applied to the 1973 and 1974 field data, almost all of the western and central basin would be considered moderately polluted. This index, however, is an arbitrary one and caution should be applied in placing absolute faith in it.

CONCLUSIONS

Lake Erie's bottom fauna has changed since 1930. During the period prior to 1953, the western basin bottom fauna was dominated by the burrowing mayfly, *Hexagenia* sp. Tubificid oligochaetes were insignificant members of the fauna except near river mouths and harbors. Currently Hexagenia is considered extinct in the western basin. Greater than 61 percent of the bottom fauna is dominated primarily by the tubificid oligochaetes of the genus *Limnodrilus*. Chironomid larvae comprise the next most abundant group with less than 20 percent of the bottom fauna. The sphaeriid clams make up less than 10 percent of the bottom fauna, except near the Detroit River where they comprise 11 to 20 percent of the bottom fauna.

The central basin fauna is likewise dominated by oligochaetes. The dominant oligochaete is *Peloscolex ferox*. However, tubificids of the genus *Limnodrilus* frequently make up significant components of the fauna and are especially important along the northern shore (11 to 30 percent of the bottom fauna). The sphaeriid clams are major components throughout the central basin, and in many cases are co-dominant with the oligochaetes. The sphaeriid clams comprise from 21 to 50 percent of the bottom fauna.

Eight percent of the bottom fauna, numerically, is comprised of the 15 "minor" taxa. These include leeches, amphipods, isopods, polychaete worms, mysids, coelenterates, flatworms, and caddisflies. Most of the numerical contributions of these taxa is due to the aquatic isopod, *Asellus racovitzai racovitzai*.

If Wright's (1955) pollution index is applied to the 1973-1974 sampling period, most of the study area would be considered moderately polluted. Caution must be exercised in trusting this index. The average density of the bottom fauna has doubled since the USPHS 1963-1964 survey with most of this change due to increases in oligochaete density.

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SECTION 11

STATISTICAL ANALYSIS OF THE 1975 INTERCOMPARISON STUDY ON LAKE ERIE

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The Ohio State University

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Center for Lake Erie Area Research
The Ohio State University

INTRODUCTION

In recent years a number of laboratories and government agencies have maintained extensive environmental monitoring programs on the Great Lakes. As part of these efforts, the Canada Centre for Inland Waters (CCIW), the Great Lakes Laboratory (GLL) of the State University of New York at Buffalo and the Center for Lake Erie Area Research (CLEAR) at The Ohio State University have ongoing monitoring programs on Lake Erie. As in the IFYGL intercomparisons (Robertson, Elder and Davies, 1974) this study attempts to assess the differences that arise between these organizations due to sampling and subsequent analysis, to determine the feasibility of combining past and future data obtained by the laboratories.

On 10 June 1975 a number of physical, chemical and biological parameters were taken at two stations four miles northeast of Conneaut, Ohio. This report discusses the statistical results of a split sample analysis on six chemical properties of the water; in particular, the results for the measures of soluble reactive phosphorus (SRP), total phosphorus (TP), total soluble phosphorus (TSP), nitrate plus nitrite (N+N), ammonia (NH_3) and total reactive silicate (SiO_2) are considered.

BACKGROUND

Three research groups are presently monitoring physical, chemical and biological parameters in Lake Erie. These groups are the Canada Centre for Inland Waters (R/V Northern Seal), Great Lakes Laboratory, State University of New York at Buffalo (R/V Dambach) and the Center for Lake Erie Area Research, Ohio State University (R/V Hydra).

On 10 June 1975 these groups sampled two stations approximately seven miles east of Conneaut, Ohio. Stations sampled included an inshore station, (3 miles off shore) designated 023 (lat. 42°02'48", long. 80°27'08") and a more lakeward station (7 miles off shore) designated 024 (lat. 42°05'54", long. 88°29'00"). Station depths were 14-14.7 m (023) and 22-22.7m (024). Sampling depths were determined via a cast bathythermograph (model OC-10/3, range 0-200').

The levels of stratification of the lake at Stations 23 and 24 at the time of the intercomparison were approximately as indicated below (Figure 141). The dots at each station represent the (nominal) sampling depths. At the time of sampling, the lake level (as measured at Erie, Pa.) was approximately 1.25 m above low water datum (LWD).

Sampling began at Station 23 at 0930 and Station 24 at 1130. The R/V Hydra anchored at both sites while the other ships did not. Apart from drift at Station 24 the ships were within 1/4 mile of each other. At Station 23 the winds were from the ENE at about 18 knots. These winds diminished to 15 knots and switched to the NE at Station 24. Waves increased from approximately one foot at Station 23 to two to three feet at Station 24 and hampered sample transfer between boats. The wind conditions at Station 24 caused the unanchored ship to drift shoreward. The study was truncated after sampling at this station and all ships returned to Conneaut Harbor to exchange samples from Station 24.

At each sampling horizon of each station 18 liters of water were taken. This volume was split into three (six liter) subsamples and exchanged among the participating groups. Containers were acid-washed and rinsed in distilled and double-distilled deionized water. Exchanges occurred immediately after sampling on Station 23 (about 1030) and approximately one hour after sampling on Station 24. All times were EST.

A list of the parameter determinations made by each of the three groups is given in Table 77. The following were selected for statistical analysis: ammonia-nitrogen, nitrate-nitrate nitrogen, soluble reactive phosphorous, total filtered phosphorous, total phosphorous (unfiltered) and total reactive silicate. Among the nutrient parameters, the phosphorous parameters are the only ones for which determinations were obtained by all three groups. The nitrogen and silicate parameters were felt to be of considerable intrinsic interest.

A summary of the operational details of the intercomparison is given in Table 78. This table contains information concerning sites,

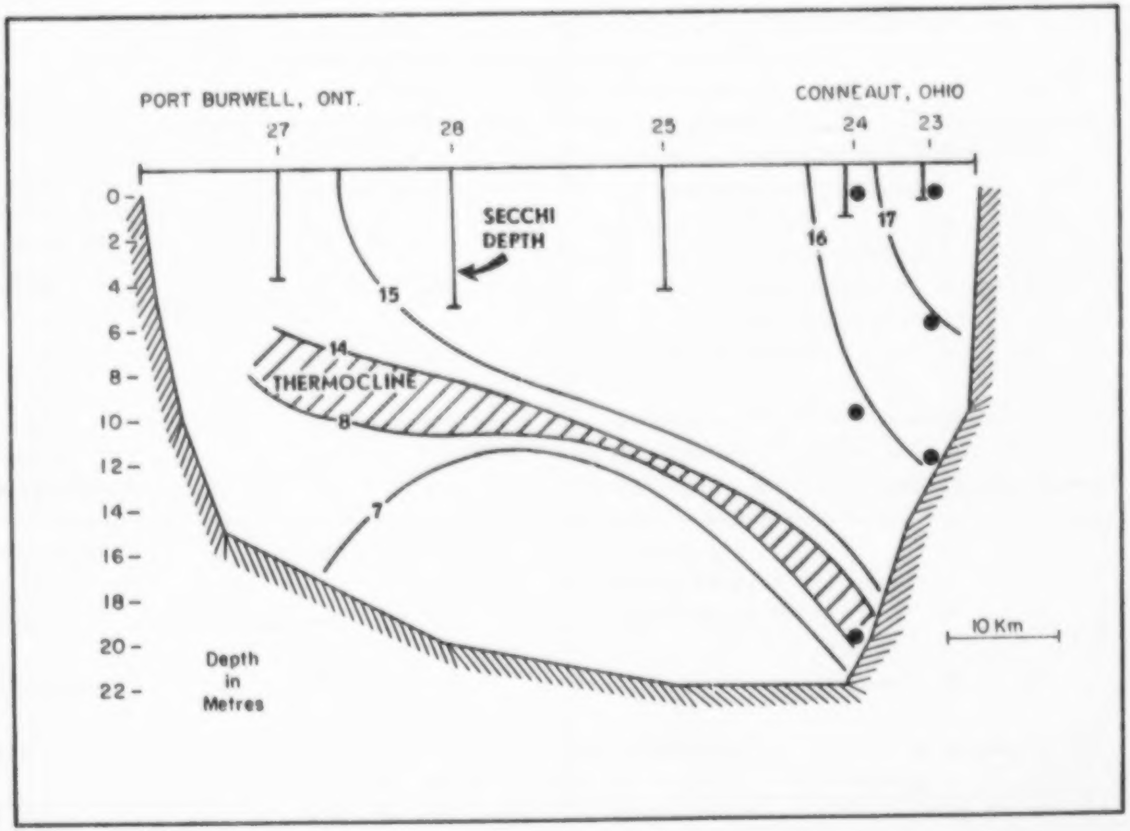

Figure 141. Temperature profile (°C) Secchi depths and sampling sites.

TABLE 77. PHYSICAL AND CHEMICAL PARAMETER DETERMINATIONS MADE BY GLL, CCIW, CLEAR

Parameter	GLL	CCIW	CLEAR	Parameter	GLL	CCIW	CLEAR
Temperature	X	X	X	Alkalinity	X	-	X
Dissolved Oxygen	X	X	X	Ammonia(NH_3)	X	-	X
Conductivity	X	X	X	Nitrate-Nitrite (NANI)	-	X	X
pH	X	X	-	Total N	-	X	-
Secchi Transp.	X	X	X	Kjeldahl N (Organic)	X	-	-
Transmittance	-	X	X	Nitrate (NO_3)	X	-	-
Chlorophyll $\frac{c}{a}$	-	X	X	Total Reactive Silicate (SiO_2)	-	X	X
Part. Organic Nitrogen	-	-	X	Soluble Reactive Phosphorus (SRPH)	X	X	X
Part. Carbon (Total)	X	-	-	Total Soluble Phosphorus (TSPH)	X	X	X
				Total Phosphorus (TOPH)	X	X	X
Part. Organic Carbon	X	X	X	Chloride	-	X	-

TABLE 78. SUMMARY OF OPERATIONAL DETAILS OF 1975 LAKE ERIE INTERCOMPARISON

		GLL	CCIW	CLEAR
Sampling Sites and Sampling Depths	023	1 7 11	1 7 13	1 7 13
	024	1 11 21	1 11 19	1 11 21
Sampling Apparatus		Water Bottle	Submersible Pump	Water Bottle and Submersible Pump
Storage				
N+N		-	None*	None*
NH_3		$HgCl_2$-4°C, plastic bottles	-	None*
SRP		4°C plastic bottles	None*	None*
TP		$HgCl_2$-4°C, plastic bottles	Sulfuric Acid-Glass bottles	100 ml glass bottles
TSP		4°C plastic bottles	Sulfuric Acid-Glass bottles	4°C glass bottles
SiO_2		-	?	4°C plastic bottles

(continued)

TABLE 78 (continued)

Analysis**		
N+N	-	Sulfanilamide, Phosphoric Acid, Napthylethylene Diamide Dihydrochloride
NH_3	Kjeldahl-Nessler's	Sodium Nitroprissuide
SRP	Ascorbic Acid Ammonium Molybdate	Stannous Chloride Ammonium Molybdate
TP	Ascorbic Acid Ammonium Molybdate	Stannous Chloride Ammonium Molybdate
TSP	Ascorbic Acid Ammonium Molybdate	Stannous Chloride Ammonium Molybdate
SiO_2	-	Oxalic Acid, Ascorbic Acid Ammonium Molybdate

---

* Samples filtered then analyzed as quickly as possible - shipboard.

** Both CCIW & CLEAR used similar equipment (Technicon AAII) and reagents, GLL employed wet lab analytical methods.

depths, sampling methodology, storage techniques, and analysis methods.

Terminology

Some terminology that is referred to in subsequent sections of the report is discussed below.

Sampling process includes overall handling of water samples from the time the ship arrives on station until the samples are divided among the groups for analysis. This consists of all aspects of obtaining the water samples, i.e., determination of sampling sites and sampling horizons, type and utilization of sampling devices and sampling containers, and conditions and duration of storage of water samples on board ship until they are subdivided for analysis.

Analysis process refers to the treatment of water samples from the time they have been subdivided and transferred to the analysis groups' ships until the final laboratory results are reported and recorded. This includes duration and methods of handling and storage of samples on board ships, methods and duration of storage and handling of samples in the laboratories, reagents and procedures utilized in the analysis process, and formulas and procedures for calculating and recording the analysis results. The mixing of reagents and execution of the laboratory tests is only a small portion of the entire analysis process. Disagreements in analysis results can be due to differences in procedures anywhere within the analysis process (for example, due to storage of samples or due to ship vs. shore laboratory analyses). A much more detailed experiment than the Lake Erie intercomparison would be necessary to separate the individual effects of the various components of the analysis process. Steps in that direction are reported by Robertson, Elder, and Davies (1974).

Sampling group is defined as that group (CLEAR, CCIW or GLL) which obtained and subdivided the water samples.

Analysis group is defined as that group (CLEAR, CCIW or GLL) which analyzed the subsamples of all samples obtained by the three sampling groups.

Subsample variation represents that portion of the variability in analytic results due only to variability in the analytic process. It excludes all effects due to variability among water samples. It is estimated from differences among the various analytic results on the same water samples (analysis group by sampling group by sampling depth mean square). Subsample variation is sometimes referred to in subsequent discussion as "subplot" variation.

Whole sample variation is the variability that enters into comparisons among sampling groups or among sampling horizons. The whole sample variation reflects both variability among different water samples as well as variability among individual analyses performed on the same water sample. The variability among water samples is due both to inherent variability in the lake water as well as to differences among the sampling processes. Estimates of whole sample variation are based on comparisons among the averages of all determinations on the same water sample (in particular, sampling group by sampling depth mean square divided by number of analysis groups). It is sometimes referred to as "whole plot" variation.

SUMMARY OF MAJOR FINDINGS

A considerable number of statistical analyses were performed on the intercomparison data. Among the conclusions arrived at are the following:

1. For each parameter but ammonia, there are statistically significant differences among analysis group average determinations. Both analysis groups report similar average determinations for ammonia, however the variabilities are rather different. At each station, the analysis group differences are especially large for soluble reactive phosphorous. (Note that a "statistically significant" difference is not necessarily a "practically significant" difference and vice versa. What is considered to be a "practically significant" difference depends heavily on the uses to which the data are to be put. A 10 percent discrepancy might be quite acceptable for some purposes but totally out of the question for others.)

2. No significant sampling group differences are evident.

3. Sampling depth effects are important especially at Station 23.

4. No systematic differences are evident between measurements on samples obtained via submersible pump or water bottles.

5. The average nutrient levels at Station 23 are consistently higher than those at Station 24. Station 23 is more shoreward thus more susceptable to shoreline processes (tributary inputs, mixing, resuspension).

6. The subsample variability is about the same at stations 23 and

24 but the whole sample variability is greater at Station 24 than at Station 23. This is probably due to the rougher surface conditions at Station 24 and the shoreward drift of two of the vessels. Both factors would contribute to heterogeneity among the water samples.

7. The variability between replicate pump determinations is generally smaller than the whole sample variability. The variation between replicate pump measurements is probably an underestimate of variability. Silicate is an exception.

Results 1 and 2 are in direct agreement with results reported by Robertson, Elder, and Davies (1974) based on a similar intercomparison that was carried out in 1972 on Lake Ontario.

Experimental Data

The experimental data are given in Table 79, which contains information about the analysis group (ANLGRP--1 = CLEAR, 2 = CCIW, 3 = GLL), sampling depth (in meters), sampling site (23 or 24), method by which CLEAR collected comparable water samples (OSUCOD--W = water bottle, A = pump replicate 1, B = pump replicate 2), soluble reactive phosphorous (SRPH), total soluble phosphorous (TSPH), total phosphorous (TOPH), nitrate-nitrite (NANI), ammonia (NH_3), and total reactive silicate (SiO_2). Of the 66 observations contained in Table 79, the 54 observations corresponding to OSUCOD = W represent the 18 CLEAR water bottle samples and the samples collected by CCIW (18) and GLL (18). These 54 observations contain all the information pertaining to comparisons among analysis groups and most of the information pertaining to comparisons among sampling groups. The primary data analyses were carried out on these 54 observations.

The CLEAR replicate pump measurements correspond to OSUCOD = A or B. There are three pairs of such replicate pump measurements at each sampling site. Comparisons between the replicate pump measurements yield information about pump sample to pump sample variability. Comparisons between the pump and water bottle measurements yield information about the presence of any systematic discrepancies between the two methods of sampling. Comparisons of CLEAR pump and water bottle measurements were carried out on these 12 observations.

Blank spaces in the various data columns correspond to missing data. For example, CCIW did not perform ammonia analyses, so that when ANLGRP = 2 the NH_3 column is blank.

TABLE 79. BASIC DATA ON SIX CHEMICAL PROPERTIES OF WATER SAMPLES

OBS	ANLGRP	SMPGRP	DEPTH	SITE	OSUCOD	SRPH	TSPH	TOPH	NANI	NH_3	SiO_2
1	1	1	1	23	W	11.7	15.0	28.0	302	58.0	340
2	1	1	7	23	W	10.9	13.3	19.8	295	61.3	320
3	1	1	13	23	W	7.6	11.0	26.6	233	51.0	320
4	2	1	1	23	W	12.0	18.0	30.0	326		310
5	2	1	7	23	W	10.0	15.0	31.0	318		290
6	2	1	13	23	W	7.8	15.0	27.0	264		280
7	3	1	1	23	W	14.2	14.2	36.1		88.0	
8	3	1	7	23	W	14.2	19.2	29.5		55.0	
9	3	1	13	23	W	15.6	16.3	25.1		55.0	
10	1	1	1	23	A	11.4		25.1	300	60.5	430
11	1	1	7	23	A	10.7		26.5	290	60.2	435
12	1	1	13	23	A	5.9		23.7	240	50.0	435
13	1	1	1	23	B	11.0		26.0	295	58.0	310
14	1	1	7	23	B	11.6		25.1	295	56.0	325
15	1	1	13	23	B	6.2		24.7	235	50.0	405
16	1	2	1	23	W	10.9	14.8	25.3	296	54.0	320
17	1	2	7	23	W	11.3	15.4	25.3	300	53.4	320
18	1	2	13	23	W	9.1	12.1	21.8	254	49.7	340
19	2	2	1	23	W	9.6	15.0	26.0	319		300
20	2	2	7	23	W	9.6	14.0	26.0	317		270
21	2	2	13	23	W	7.5	12.0	26.0	270		270
22	3	2	1	23	W	14.9	14.9	33.2		53.0	
23	3	2	7	23	W	15.6	20.6	32.4		60.0	
24	3	2	13	23	W	9.8	12.0	30.2		28.0	
25	1	3	1	23	W	11.7	15.6	27.8	302	59.0	300
26	1	3	7	23	W	11.8	14.8	32.2	288	56.5	300
27	1	3	13	23	W	7.7	11.0	25.0	240	51.0	300

(continued)

TABLE 79 (continued)

OBS	ANLGRP	SMPGRP	DEPTH	SITE	OSUCOD	SRPH	TSPH	TOPH	NANI	NH_3	SiO2
28	2	3	1	23	W	11.0	18.0	31.0	324		340
29	2	3	7	23	W	11.0	19.0	30.0	319		310
30	2	3	13	23	W	7.5	14.0	29.0	252		270
31	3	3	1	23	W	15.6	15.6	30.2		61.0	
32	3	3	7	23	W	14.2	15.6	33.2		59.0	
33	3	3	13	23	W	15.6	15.6	23.6		42.0	
34	1	1	1	24	W	4.6	8.6	19.4	201	36.5	230
35	1	1	11	24	W	1.6	5.6	14.6	207	31.3	175
36	1	1	21	24	W	2.5	11.6	22.6	347	45.7	370
37	2	1	1	24	W	3.8	8.9	19.0	216		220
38	2	1	11	24	W	1.3	6.5	17.0	223		170
39	2	1	21	24	W	1.8	8.0	23.0	381		310
40	3	1	1	24	W	6.3	6.3	17.8		39.0	
41	3	1	11	24	W	7.0	7.0	10.7		28.0	
42	3	1	21	24	W	5.6	7.7	16.4		44.0	
43	1	1	1	24	A	5.0		19.4	202	38.1	325
44	1	1	11	24	A	2.1		16.3	172	27.3	325
45	1	1	21	24	A	1.4		17.2	248	46.5	255
46	1	1	1	24	B	5.5		15.3	210	36.5	450
47	1	1	11	24	B	2.3		19.5	207	31.4	270
48	1	1	21	24	B	2.5		17.2	305	57.7	195
49	1	2	1	24	W	2.7	7.9	18.2	162	29.0	240
50	1	2	11	24	W	2.1	6.2	13.6	206	34.2	190
51	1	2	21	24	W	2.2	6.2	14.6	245	35.0	215
52	2	2	1	24	W	2.3	8.0	17.0	171		180
53	2	2	11	24	W	1.7	6.9	17.0	232		150
54	2	2	21	24	W	2.0	8.0	15.0	268		200
55	3	2	1	24	W	5.6	5.6	17.1		39.0	

(continued)

TABLE 79 (continued)

OBS	ANLGRP	SMPGRP	DEPTH	SITE	OSUCOD	SRPH	TSPH	TOPH	NANI	NH_3	SiO_2
56	3	2	11	24	W	7.0	7.7	16.4		24.0	
57	3	2	21	24	W	6.3	7.0	18.4		15.0	
58	1	3	1	24	W	4.9	8.3	49.5	208	35.5	300
59	1	3	11	24	W	2.0	5.3	17.1	195	33.8	225
60	1	3	21	24	W	2.3	5.6	16.7	242	36.0	325
61	2	3	1	24	W	4.7	12.0	21.0	230		260
62	2	3	11	24	W	2.0	7.7	15.0	212		170
63	2	3	21	24	W	2.0	5.6	12.0	264		170
64	3	3	1	24	W	6.6	7.2	17.8		44.0	
65	3	3	11	24	W	7.7	7.7	10.7		58.0	
66	3	3	21	24	W	5.6	5.6	16.4		28.0	

Experimental Results

A considerable number of statistical analyses and data displays were carried out on the intercomparison data. The main conclusions from these analyses were summarized in the section titled "Summary of Major Findings". This section contains a more extensive, but still relatively brief and non technical discussion of the bases of the conclusions.

The principal result of this section is statistical evidence of differences among analysis groups but not among sampling groups. This is in direct agreement with results reported by Robertson, Elder, and Davies (1974) based on a similar intercomparison that was carried out in 1972 on Lake Ontario.

The intercomparison experiment was carried out at two sampling stations (23 and 24) on Lake Erie. Because the horizon depths and nutrient levels at the two sites were quite different and since the whole sample variability at Station 24 exceeded that at Station 23 (for some considerably), the data from each of the two stations was analyzed separately. Thus, no variance estimates have been pooled across stations. Some comparisons (particularly those involving analysis groups) might be reexamined with variance estimates pooled across stations, for instance where pooling seems sensible. The increased degrees of freedom might increase the sensitivity of the tests.

In the course of several of the analyses, it appeared from the data that certain determinations might be out line relative to the rest. In such cases the data were reanalyzed after omitting the suspect value or values. The results of both the original and the reanalyses are reported.

Overall Average Values. Table 80 contains the overall average values by station of each of the six nutrients. The averages are taken over analysis group, sampling group, and sampling depth. It is immediately evident that the average values are consistently higher at site 23 than at site 24. The discrepancies between the two sites vary from 19 percent to 66 percent of the site 23 average values.

This observation is in agreement with other data collected. Station 23 is more shoreward, thus more susceptable to shoreline processes (tributary inputs, mixing, sediment resuspension). Indeed, it appears that Station 23 is located deeper within a nutrient rich surface plume (see Figure 141 and section on sampling depth effects) than Station 24.

TABLE 80. OVERALL AVERAGE DETERMINATIONS BY SITE

Parameter (ppb)	Site 23 Avg.	Site 24 Avg.	Difference
Soluble reactive phosphorus	11.42 (11.48*)	3.86	7.56 (7.62*)
Total soluble phosphorus (filtered)	15.07	7.36	7.71
Total phosphorus (unfiltered)	28.57	17.93 (16.71**)	10.64 (11.86**)
Nitrate - nitrite	289.94	233.89	56.05
Ammonia	55.27 (54.93**)	35.33	19.94 (19.6***)
Silicate	305.56	227.78	77.78

* Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.
** Reanalysis of site 24 total phosphorus data after deleting observation 58.
*** Reanalysis of site 23 ammonia data after deleting observation 7 and 24.

Whole Sample, Subsample, and Pump to Pump Variability. The intercomparison is an example of a split plot experiment. Comparisons of analysis groups are made within the same water samples whereas comparisons of sampling groups, depths, or sites are made among different water samples. Thus comparisons of sampling groups or sampling depths reflect whole sample variation whereas comparisons of analysis groups reflect only subsample variation. This implies that different comparisons require different error yardsticks.

In addition to whole sample and subsample variability, another variability estimate can be obtained by comparing the determinations based on the replicate CLEAR pump samples. Conceptually, these pump to pump variability estimates should approximately agree with or exceed the whole sample errors, but except for silicate they turn out to be about half the value. Table 81 contains the estimated whole sample, subsample, and pump to pump variances of each of the six chemical properties, by site. Beside each variance estimate is the degrees of freedom on which it is based. A number of comparisons can be made from the table.

1. The whole sample variance estimates are consistently greater at Station 24 than at Station 23. Although it is difficult to compare variances based on just four degrees of freedom, there is some evidence of greater whole sample variation at Station 24 than at Station 23.

2. Except for silicate, there is no evidence of greater subsample variation at one station than at another.

3. There is some suggestion that pump to pump variation is greater at Station 24 than at Station 23, although the evidence is weaker than that for whole sample variations.

4. With the exception of silicate, the whole sample variation is one and one half to three times the pump to pump variation.

Analysis Group Effects. The average determinations for the three analysis groups (averaged over sampling group and depth) were obtained and compared at each site. Table 82 contains, for each of the six chemical properties, the three analysis group averages, the estimated standard errors (based on the subsample variation) appropriate for assessing differences between pairs of averages, and the significance levels at which the averages are significantly diffferent.

At site 23 the analysis group averages differ significantly for all parameters but ammonia. (The ammonia determinations differ in variability but not in average value.) At site 24 there is statistical evidence

TABLE 81. SUBSAMPLE, WHOLE SAMPLE, PUMP-TO-PUMP VARIANCES - BY SITE

Station 23

Property	Subsample Variation	d.f.	Whole Sample Variation	d.f.	Pump to Pump Variation	d.f.
soluble reactive phosphorous	2.62(0.24*)	8(7*)	0.27(0.31*)	(4*)	0.18	3
total soluble phosphorous (filtered)	3.16	8	0.60	4	no pump samples	
total phosphorous (unfiltered)	3.71	8	1.55	4	0.63	3
nitrate-nitrite	27.47	4	36.24	4	12.5	3
ammonia	82.31 (40.20***)	4 (2***)	23.02 (6.84***)	4 (4***)	3.98	3
silicate	122.22	4	77.78	4	4566.67	3

Station 24

Property	Subsample Variation	d.f.	Whole Sample Variation	d.f.	Pump to Pump Variation	d.f.
soluble reactive phosphorous	0.10	8	0.36	4	0.25	3
total soluble phosphorous (filtered)	0.98	8	1.87	4	no pump samples	
total phosphorous (unfiltered)	27.47(4.38**)	(7**)	22.71(4.80**)	(4**)	4.51	3
nitrate-nitrite	28.22	4	1441.35	4	756.33	3
ammonia	65.72	4	59.23	4	24.14	3
silicate	899.31	4	1949.66	4	3708.33	3

* Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.

** Reanalysis of site 24 total phosphorus data after deleting observation 58.

*** Reanalysis of site 23 ammonia data after deleting observation 7 and 24.

TABLE 82. ANALYSIS GROUP AVERAGES - BY SITE

Property	Analysis Group Averages			Std. Err. of		Significance
	CLEAR	CCIW	GLL	Difference	d.f.	Level
Station 23						
sol. react. phos.	10.30	9.56	14.41	.765	8	.0008
	(10.30*)	(9.56*)	(15.31*)	(+)	(7*)	(.0001*)
tot. sol. phos. (filtered)	13.67	15.56	16.00	.838	8	.05
tot. phos. (unfiltered)	26.87	28.44	30.39	.905	8	.01
nitrate-nitrite	278.89	301.00	--	2.47	4	.002
ammonia	54.88	--	55.67	4.27	4	.86
	(54.88***)	--	(54.75***)	(3.54+++)	(2***)	(.97***)
silicate	317.78	293.33	--	5.22	4	.01
Station 24						
sol. react. phos.	2.77	2.40	6.41	.147	8	.0001
tot. sol. phos. (filtered)	7.26	7.96	6.87	.466	8	.12
tot. phos. (unfiltered)	20.70	17.33	15.74	2.47	8	.18
	(17.89**)	(17.33**)	(15.74**)	(++)	(7**)	(.20**)
nitrate-nitrite	223.67	244.11	--	2.50	4	.002
ammonia	35.22	--	35.44	3.82	4	.96
silicate	252.22	203.33	--	14.14	4	.03

* Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.

** Reanalysis of site 24 total phosphorus data after deleting observation 58.

*** Reanalysis of site 23 ammonia data after deleting observations 7 and 24.

+ After reanalysis std. err. of CLEAR, CCIW diff = 0.232; std err of CLEAR, GLL and CCIW, GLL diffs = 0.253

++ After reanalysis std. err. of CLEAR, CCIW and CLEAR, GLL diffs = 1.075; std. err. of CCIW, GLL diff = 0.986

+++ After reanalysis

of analysis group differences for soluble reactive phosphorous, nitrate-nitrite, and silicate. At both sites the analysis group differences are especially large for soluble reactive phosphorous.

Several of the discrepancy patterns are consistent between sites. GLL's soluble reactive phosphorous levels are relatively high at both sites. CLEAR's nitrate-nitrite levels are smaller than CCIW's and CLEAR's silicate levels are greater than CCIW's at both sites. CLEAR's ammonia levels have the same mean but are less variable than GLL's at both sites.

Sampling Group Effects. The average determinations for the three sampling groups (averaged over analysis group and depth) were obtained and compared at each site. Table 83 contains, for each of the six chemical properties, the three sampling group averages, their estimated standard errors (based on the whole sample variation), and the significance levels at which they are significantly different.

As can be seen from Table 83 no significant sampling group effects are evident at either site.

Sampling Depth Effects. The average determinations for the three sampling depths (averaged over analysis group and sampling group) were obtained and compared for each site. Table 84 contains, for each of the six chemical properties, the three sampling depth averages, their estimated standard errors (based on the whole sample variation), and the significance levels at which they are significantly different.

At site 23 significant depth effects are evident for all six chemicals properties. There is consistently a sharp drop in nutrient levels between 7 and 13 meters.

At site 24 the depth effects are either nonsignificant or at best marginally significant. This is due to a combination of higher standard errors at site 24 (especially for nitrate-nitrite, ammonia, and silicate) and less pronounced changes with depth.

It is interesting to note the drop in concentration levels between 1 meter and 13 meters at Station 23 and (with the exception of nitrate-nitrite) a similar drop in concentration levels between 1 meter and 11 meters at Station 24. However, at Station 24 the concentration levels remain the same or actually rise between 11 meters and 21 meters.

Comparison of Pump and Water Bottle Samples Collected and Analyzed by CLEAR. Water samples can be collected either by a submersible pump or by water bottle samplers. In order to determine

TABLE 83. SAMPLING GROUP AVERAGES - BY SITE

Property	Sampling Group Averages CLEAR	CCIW	GLL	Std. Err. of Difference	d.f.	Significance Level
Station 23						
sol. react. phos.	11.56	10.92	11.79	0.42	4	.22
	(11.56*)	(11.82*)	(11.79*)	(+)	(4*)	(.75*)
tot. sol. phos. (filtered)	15.22	14.53	15.47	0.64	4	.40
tot. phos. (unfiltered)	29.23	27.36	29.11	1.02	4	.23
nitrate-nitrite	289.67	292.67	287.50	4.92	4	.61
ammonia	61.38	49.68	54.75	3.92	4	.10
	(56.23***)	(53.46***)	(54.75***)	(+++)	(4***)	(.70***)
silicate	310.00	303.33	303.33	7.20	4	.61
Station 24						
sol. react. phos.	3.83	3.54	4.20	0.48	4	.53
tot. sol. phos. (filtered)	7.80	7.06	7.22	1.12	4	.79
tot. phos. (unfiltered)	17.83	16.37	19.58	3.89	4	.73
	(17.83**)	(16.37**)	(17.21**)	(++)	(4**)	(.70**)
nitrate-nitrite	262.50	214.00	225.17	31.00	4	.36
ammonia	37.42	29.37	39.22	6.28	4	.35
silicate	245.83	195.83	241.67	36.05	4	.40

* Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.

** Reanalysis of site 24 total phosphorus data after deleting observation 58.

*** Reanalysis of site 23 ammonia data after deleting observations 7 and 24.

+ After reanalysis std err of CLEAR, GLL diff = 0.452; std err of CLEAR, CCIW and CCIW, GLL diffs = 0.492

++ After reanalysis std err of CLEAR, CCIW diff = 1.79; std err of CLEAR, GLL, and CCIW, GLL diffs = 1.95

+++ After reanalysis std err of CLEAR, CCIW diff = 3.02; std err of CLEAR, GLL, and CCIW, GLL diffs = 2.53

TABLE 84. SAMPLING DEPTH AVERAGES - BY SITE

Property	Sampling Depths Averages			Std Err of Difference	d.f.	Significance Level
	1 meter	7 meter	13 meter			
Station 23						
sol. react. phos.	12.40	12.07	9.80	0.42	4	0.008
	(12.40*)	(12.07*)	(10.70*)	(+)	(4*)	(0.05)
tot. sol. phos. (filtered)	15.68	16.32	13.22	0.64	4	0.02
tot. phos. (unfiltered)	29.73	29.93	26.03	1.02	4	0.03
nitrate-nitrite	311.50	306.17	252.17	4.92	4	0.002
ammonia	62.17	57.53	46.12	3.92	4	0.04
	(57.01**)	(57.53***)	(49.90**)	(+++)	(4***)	(0.09***)
silicate	318.33	301.67	296.67	7.20	4	0.08
	1 meter	7 meter	13 meter			
Station 24						
sol. react. phos.	4.61	3.60	3.37	0.48	4	0.12
tot. sol phos. (filtered)	8.09	6.73	7.26	1.12	4	0.53
tot. phos. (unfiltered)	21.87	14.68	17.23	3.89	4	0.28
	(19.06**)	(14.68**)	(17.23**)	(++)	(4**)	(0.20**)
nitrate-nitrite	198.00	212.50	291.17	31.00	4	0.08
ammonia	37.17	34.88	33.95	6.28	4	0.87
silicate	238.33	180.00	265.00	36.05	4	0.17

Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.

** Reanalysis of site 24 total phosphorus data after deleting observation 58.

*** Reanalysis of site 23 ammonia data after deleting observations 7 and 24.

+ After reanalysis std err of CLEAR, GLL diff = 0.452; std err of CLEAR, CCIW, and CCIW, GLL diffs = 0.492

++ After reanalysis std err of CLEAR, CCIW diff = 1.79; std err CLEAR, GLL and CCIW, GLL diffs = 1.95

+++ After reanalysis std err of CLEAR, CCIW diff = 3.02; std err CLEAR, GLL and CCIW, GLL diffs = 2.53

whether any systematic effects are introduced by the method of sampling, CLEAR collected two pump samples and a water bottle sample at each of the six site-depth combinations. Comparison of the replicate pump measurements provides direct information about pump sample to pump sample variability. Comparison of pump and water bottle measurements provides information concerning the existence of systematic effects due to sampling method. The analysis results are summarized in Table 85. This table shows that with the exception of silicate, the pump to pump variability is consistently smaller than the whole sample variation and the pump to pump variation at site 23 is smaller than that at site 24.

The "t-ratio" column summarizes the statistics to test for systematic differences between the two sampling methods. The t-ratio is formed by dividing the difference between average pump determination and water bottle determination by an estimate of its standard error based on pump to pump variation. Where the pump to pump variation is similar between sites, the 3 degrees of freedom variance estimates at each site are pooled to form a more precise 6 degrees of freedom variance estimate. Generally speaking, no significant systematic differences between the two sampling methods are apparent. However inferences based on just three degrees of freedom or even six are not very powerful.

DISCUSSION

A number of questions and issues arose in the process of analyzing the data. Several of these are indicated below:

1. A number of determinations were identified that seemed to be out of line. These were sometimes isolated determinations, but also sometimes involved all the determinations from the same water sample. Where possible outliers are present, the basic data should be reviewed to determine whether or not the suspect data are erroneous and if so, why. Are the outlying values due to clerical errors, error in the analysis procedure, errors in mixing or calibrating reagents, or mixups in samples? Can the appropriate values be determined? Are these "out of line" observations just normal variation?

2. Why is the variation between replicate pump samples generally smaller than the whole sample variation? Which, if either, is a true estimate of sample to sample variation? Why is this relationship reversed for silicate?

3. There was some confusion about sampling depths at the bottoms of both stations. At Station 23, both CLEAR and CCIW report

TABLE 85. COMPARISON OF CLEAR PUMP AND WATER BOTTLE MEASUREMENTS - BY SITE

Properties	Pump Average	Water Bottle Msmnt.	Pump to Pump Var.	Whole Sample Variation	t-ratio	d.f.	Significance Level
Station 23							
Soluble reactive phosphorus	9.4667	10.0667	0.18	0.31*	-1.82	6	0.12
Total soluble phosphorus (filtered)	no pump sample determinations made						
Total phosphorus (unfiltered)	25.1833	28.133	0.63	1.55	-5.27	3	0.014
Nitrate-nitrite	275.8333	276.6667	12.5	36.24	-0.33	3	0.76
Ammonia	55.78	56.77	3.98	6.84***	-0.70	3	0.54
Silicate	390.00	326.67	4566.67	77.78	1.39	6	0.22
Station 24							
Soluble reactive phosphorus	3.1333	2.9000	0.25	0.36	0.706	6	0.50
Total soluble phosphorus (filtered)	no pump sample determinations made						
Total phosphorus (unfiltered)	17.4833	18.8667	4.51	4.80**	-0.92	3	0.44
Nitrate-Nitrite	224.0000	251.6667	756.33	1441.35	-1.422	3	0.26
Ammonia	39.58	37.83	24.14	59.23	0.50	3	0.66
Silicate	303.33	258.33	3708.33	1949.66	0.99	6	0.36

* Reanalysis of site 23 soluble reactive phosphorus data after deleting observation 24.

** Reanalysis of site 24 total phosphorus data after deleting observation 58.

*** Reanalysis of site 23 ammonia data after deleting observations 7 and 24.

sampling at 13 meters whereas GLL reports sampling at 11 meters. At Station 24, both CLEAR and GLL report sampling at 21 meters whereas CCIW reports sampling at 19 meters. These discrepancies in sampling depths were ignored for the purpose of this analysis, however they could possibly introduce bias or variability into the data. This should be kept in mind when preparing protocols for future intercomparisons.

4. Generally speaking, the sampling variation at Station 24 was larger than that at Station 23, sometimes substantially so. Does heterogeneity of samples vary substantially from station to station? If so, this should be taken into account when designing future sampling procedures and when analyzing the data.

5. It would be useful to repeat the intercomparison at several distinct points in time, for instance, weeks or months apart, and to incorporate more replication at each time. This would provide information as to whether there is time to time random variation of the results within laboratories and as to whether the discrepancies between laboratories are random or systematic. The separation of systematic and random sources of variation might give clues about their nature, thereby enabling sources of variation to be eliminated. See Robertson, Elder, and Davies (1974) for an example of this.

REFERENCE

Robertson, Andrew, Floyd Elder and Tudor Davies. 1974. IFYGL chemical intercomparisons. Proc. 17th Conf. Great Lakes Res. Internat. Assoc. Great Lakes Res. p. 682-696.

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16. ABSTRACT

A three-year assessment of nutrient control efforts was conducted in the western and central basins of Lake Erie during the period June 1973 to June 1976. The objective of the study was to determine recent trends in lake eutrophication and water quality which may be related to recent attempts to control nutrient loadings to these basins. The assessment was accomplished by visiting approximately 50 stations at nearly monthly intervals during the ice-free periods. Over 25 water quality, meteorologican and biological parameters were routinely determined shipboard or on samples collected at a typical station. Measurements were taken at several depths in order to characterize the various strata of water in the lake and to permit volume-weighted calculation of nutrient concentrations and quantities. Data from previous limnological surveys as far back as 1928 were compared with the results of the present study to establish longterm trends, as well as recent trends since the last comprehensive survey in 1970.

The fundamental conclusion of this assessment is that during the first half of this decade no significant decrease in the loading of nutrients to Lake Erie has taken place. Therefore, during this period the concentrations and quantities of nutrients within the waters of the lake have remained relatively stable. An encouraging sign of nutrient control is that although no decreases have been observed, the constant increases which have taken place in preceeding decades have been stopped.

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